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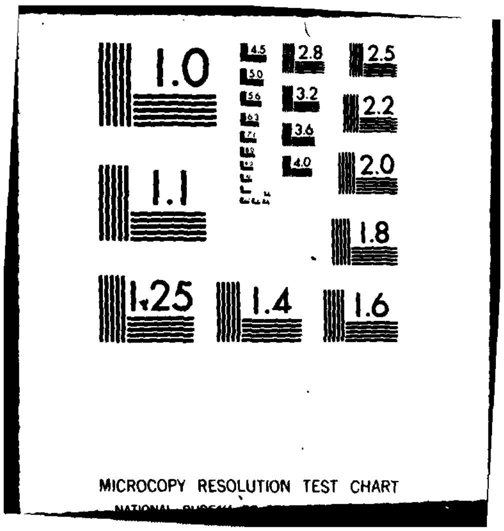
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LEVEL II

INFLUENCE OF NOISE REDUCTION ON WEIGHT AND COST OF GENERAL AVIATION PROPELLERS

ADA082120

Robert J. Klatte
Frederick B. Metzger

JUNE 1979
Final Report

U.S. DEPARTMENT OF TRANSPORATION
FEDERAL AVIATION ADMINISTRATION
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16. Abstract

Results of a study are reported in which the influence of noise reduction on weight and cost of propellers used in General Aviation aircraft was evaluated. Aircraft performance was not to be degraded by installation of the reduced noise propellers. Only propeller modifications were permitted. Engine modifications, such as introduction of a gearbox to reduce noise by reduction of RPM, were not permitted in the study. Major factors in noise reduction found promising in the study were (1) optimization of performance by use of the best available airfoils, (2) use of thin airfoils and a narrow elliptical tip blade planform, and (3) increasing the number of blades consistent with maintaining aircraft performance. For the three aircraft studied (a single engine, a light twin and a heavy twin) the flyover noise reduction potential varied from 3 to 8 dBA with no weight or cost penalty. Greater reductions in noise resulted in increased weight and/or cost penalties. Also, in some cases, engine noise would have to be reduced to achieve greater reductions. The progress by General Aviation aircraft manufacturer's in reducing noise is indicated by the finding that the most recent aircraft design had the smallest noise reduction potential.

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SUMMARY

A study of the propeller weight and cost penalties associated with reducing the noise of General Aviation aircraft has been conducted. In the study, the basic assumption was that performance of the noise reduced aircraft would not differ from the standard aircraft. Also, engine modifications such as introducing a gearbox for RPM reduction were not permitted in the study. Three aircraft were studied; a single engine, a light twin, and a heavy twin. The single engine aircraft (Beech 35-B33 Debonair) was studied in depth to develop the most promising noise reduction concepts. Then these concepts were applied to the light twin (Beech 76 Duchess) and heavy twin (de Havilland DHC-6 Twin Otter) aircraft. For each aircraft the accuracy of the noise prediction methodology used in the study was confirmed by comparing predictions with flyover measurements. The most promising noise reduction concepts were found to be (1) diameter reduction associated with optimization of performance by use of the best available airfoils, (2) use of thin airfoils and a narrow elliptical planform near the tip of the blades, and (3) increasing the number of blades consistent with maintaining takeoff and cruise performance.

More complex modifications to the blade tips were also considered, which consisted of bent tips or tip plates and blade tip sweep. The available performance prediction methodology indicates that bent tips or tip plates have the potential for some improvement in performance but this could be offset by increases in drag. If performance improvements could be achieved, then noise could be reduced by reducing diameter. Also, some limited work indicates that noise might be reduced by cancellation of noise sources. However, bent tips or tip plates are not considered promising until further analytical and experimental work is conducted. Blade sweep was also considered as a noise reduction concept. Blade tips with sufficient sweep to produce substantial noise reductions required structural design and cost studies which were beyond the scope of the present contract. With smaller sweep angles, the noise reduction benefits were less than those which can be achieved with the modifications mentioned above. If greater noise reductions are required than can be achieved with the modifications described above, then further work appears warranted to evaluate the potential of swept tips.

Three noise reduction goals were established for the study: (1) the maximum noise reduction that can be achieved before engine noise suppression becomes necessary, (2) the noise reduction that can be achieved without a weight or cost penalty, and (3) the maximum noise reduction that can be achieved without an aircraft performance penalty. The maximum noise reduction that can be achieved before engine noise suppression becomes necessary is 11.1 dBA for the single engine Debonair, 3.8 dBA for the light twin Duchess, and 5.5 dBA for the Twin Otter. The low noise level of the turbine engines of the Twin Otter allow reduction of propeller noise to the point where aircraft performance would be degraded without engine noise becoming significant.

The maximum propeller noise reduction that can be achieved without a weight or cost penalty is 11.1 dBA for the Debonair, 3.8 dBA for the Duchess, and 5.5 dBA for the Twin Otter. In every case, this reduction was achieved with a reduced diameter propeller with thin elliptical tips and NACA Series 16 airfoils. For the noise reduction propellers, the number of blades was 2 for the Debonair, 4 for the Duchess, and 4 for the Twin Otter.

The maximum propeller noise reduction that can be achieved without aircraft performance penalty is 13.7 dBA for the Debonair, 8.6 dBA for the Duchess, and 5.5 dBA for the Twin Otter. In every case, this reduction was achieved with a reduced diameter propeller with thin elliptical tips and NACA Series 16 airfoils. For the noise reduction propellers, the number of blades was increased to 3 for the Debonair, 4 for the Duchess, 4 for the Twin Otter. These configurations generally weighed more and cost more than the existing propellers on the aircraft.

The variation in noise reduction level found in this study indicates that further evaluation of the complete General Aviation fleet would be required to establish the cost and weight impact of any proposed reduction in current certification levels. Also, the noise reductions, costs, and weights calculated for this report must be confirmed by further work both analytical and experimental.

SYMBOLS AND ABBREVIATIONS

A - Wing aspect Ratio (Wing Average Chord^2/Wing Surface area)

AF - Propeller Activity Factor, $\frac{100,000}{16} \int_{SCO}^{1.0} \frac{b}{D} x^3 \, dx$

b - Blade Section Width, ft

BPF - Blade Passage Frequency, Cycles per Second

C_{D_c} - Combined Drag Coefficient for Nacelle and Fuselage for Single Engine Aircraft

C_{D_e} - Drag Coefficient for Aircraft Empennage

C_{D_F} - Drag Coefficient for Aircraft Fuselage

$C_{D_{GR}}$ - Drag Coefficient for Aircraft Landing Gear

C_{D_n} - Drag Coefficient for Aircraft Engine Nacelle

C_{D_w} - Drag Coefficient for Wing

$C_{D_{wo}}$ - Drag Coefficient for Wing at Zero Lift

C_L - Lift Coefficient

C_{L_i} - Propeller Blade Integrated Design Lift Coefficient, $4 \int_{SCO}^{1.0} C_L \, x^3 \, dx$

D - Propeller Diameter, ft

dB - Noise Level in Decibels, with a reference of 20 μPa (0.0002 dynes/cm^2)

dBA - A-Weighted Noise Level in Decibels, with a reference of 20 μPa (0.0002 dynes/cm^2)

e - Airplane Efficiency Factor

EPNL - Effective Perceived Noise Level, Decibels

h - Maximum Blade Section Thickness, ft

h/b - Max Section Thickness/Section Width

HSD - Hamilton Standard Division

H_z - Hertz, Cycles per Second

M_N - Mach Number

P_a - Pascal

PNL - Perceived Noise Level, Decibels

PNLT - Tone Corrected Perceived Noise Level, Decibels

q_o - Dynamic Pressure Based on Forward Flight Velocity, $1/2\rho \, (V_o)^2$

q_{ss} - Dynamic Pressure Based on Slip Stream Velocity, $1/2\rho \, (V_{ss})^2$

r - Propeller Radius, ft

R_t - Propeller Tip Radius, ft

RPM - Revolutions per Minute

SCO - Spinner Cutoff or Hub diameter/Propeller diameter

SYMBOLS AND ABBREVIATIONS (Cont'd)

SHP	-	Shaft Horsepower
SHP/D^2	-	Shaft Horsepower/Diameter^2
SPL	-	Sound Power Levels, dB
V_o	-	Forward Flight Velocity, ft/sec
V_{ss}	-	Slip Stream Velocity, ft/sec
x	-	Fraction of Propeller Tip Radius, r/R_t
ρ	-	Density of Air, lb_m/ft^3

INTRODUCTION

On February 7, 1975 Appendix F of Federal Aviation Regulations Part 36, Noise Standards: Aircraft Type and Airworthiness Certification became effective. This regulation prescribes the limiting noise levels and procedures for measuring noise of General Aviation propeller driven aircraft up to 12,500 lbs. gross weight. Noise measurements are made with a microphone mounted 4 ft above the ground with the aircraft flying over at 1000 ft altitude at the speed associated with highest power in the normal operating range. A performance correction is made which allows higher noise levels for aircraft with short takeoff, roll and high climb rates. For aircraft certified after January 1, 1980 the performance corrected A-Weighted sound pressure levels have been established.

The aircraft in ghe General Aviation fleet at the present time represent various levels of noise control technology. Noise control was not given high priority in aircraft designed prior to 1975. Since then, the General Aviation aircraft manufacturers have begun to consider flyover noise level as one of the design requirements both because of the noise certification requirements and because of the concern expressed by the public around airports in Europe and the United States.

In the past, the methodology for study of the impact of noise reduction on weight and cost of a propeller was more or less limited. However, with interest in the advanced turboprop (Prop-Fan) for application to large fuel efficient high speed transport aircraft, new noise prediction methodology has become available. This has been used in conjunction with well proven performance prediction methodology and weight and cost prediction methodology derived from existing General Aviation propellers to conduct the study summarized in this report.

The basic requirements for the study were that noise reduction propellers were to be defined which would not degrade the existing performance of the aircraft being evaluated. No engine changes such as gearbox additions were permitted. For various promising configurations, the weight and cost impact of noise reduction was calculated.

Initially the accuracy of the noise prediction methodology was evaluated by comparison of predictions with the available test data for the three aircraft selected for study; the single engine Beech 35-B33 Debonair, the light twin engine Beech Duchess and the heavy twin engine De Havilland Twin Otter. These comparisons confirmed the accuracy of the method. Then an in-depth study of the Debonair was conducted to establish the most promising noise reduction configurations. These configurations were the basis of studies of the Duchess and Twin Otter. The results of the studies indicate that there is potential for noise reduction of existing aircraft but the more recently designed aircraft appear closer to the noise "floor" established by engine noise than older aircraft.

DISCUSSION

Introduction

In conducting the General Aviation Propeller Study the initial task was the confirmation of the accuracy of the noise prediction methodology to be used. This was done by predicting the A-weighted sound pressure level and peak noise spectrum (at flyover conditions similar to those used for noise certification) by use of the new Far Field Propeller Noise Prediction procedure discussed in Appendix A and comparing these predictions with the best available test data. For the single engine aircraft study the noise predictions were compared with measurements for the Piper PA28-20 Arrow II and the Beech 35-B33 Debonair. For the light twin, the comparisons were made for the Beech 76 Duchess. For the heavy twin, the comparisons were made for the De Havilland DHC-6 Twin Otter. The levels for these four aircraft are shown along with other General Aviation aircraft as a function of gross weight in Figure 1. The single engine aircraft are typical of well established older designs which might benefit from current technology propeller designs. The light twin Beech Duchess is an example of a recent technology design which should already incorporate much of the current noise control technology. The heavy twin De Havilland Twin Otter is typical of the earlier technology aircraft which are in wide use as executive transports and commuter aircraft.

After the methodology was confirmed an in-depth study of noise reduction concepts was conducted using the Beech 35-B33 Debonair as the reference aircraft. The most promising concepts from this study were used then in studies of the light twin Beech 76 Duchess and the heavy twin De Havilland DHC-6 Twin Otter.

In the studies of these three aircraft the propeller performance prediction methodology (discussed in Appendix B), the propeller weight prediction methodology (discussed in Appendix C) and propeller cost prediction methodology (discussed in Appendix D) were used. One of the most promising noise reduction concepts studied was the reduction in diameter (and resulting reduction in tip speed). This modification increases slipstream velocity and therefore aircraft drag. Consequently, as diameter is reduced the required propeller thrust increases. The methodology used in evaluating this increased thrust is discussed in Appendix E.

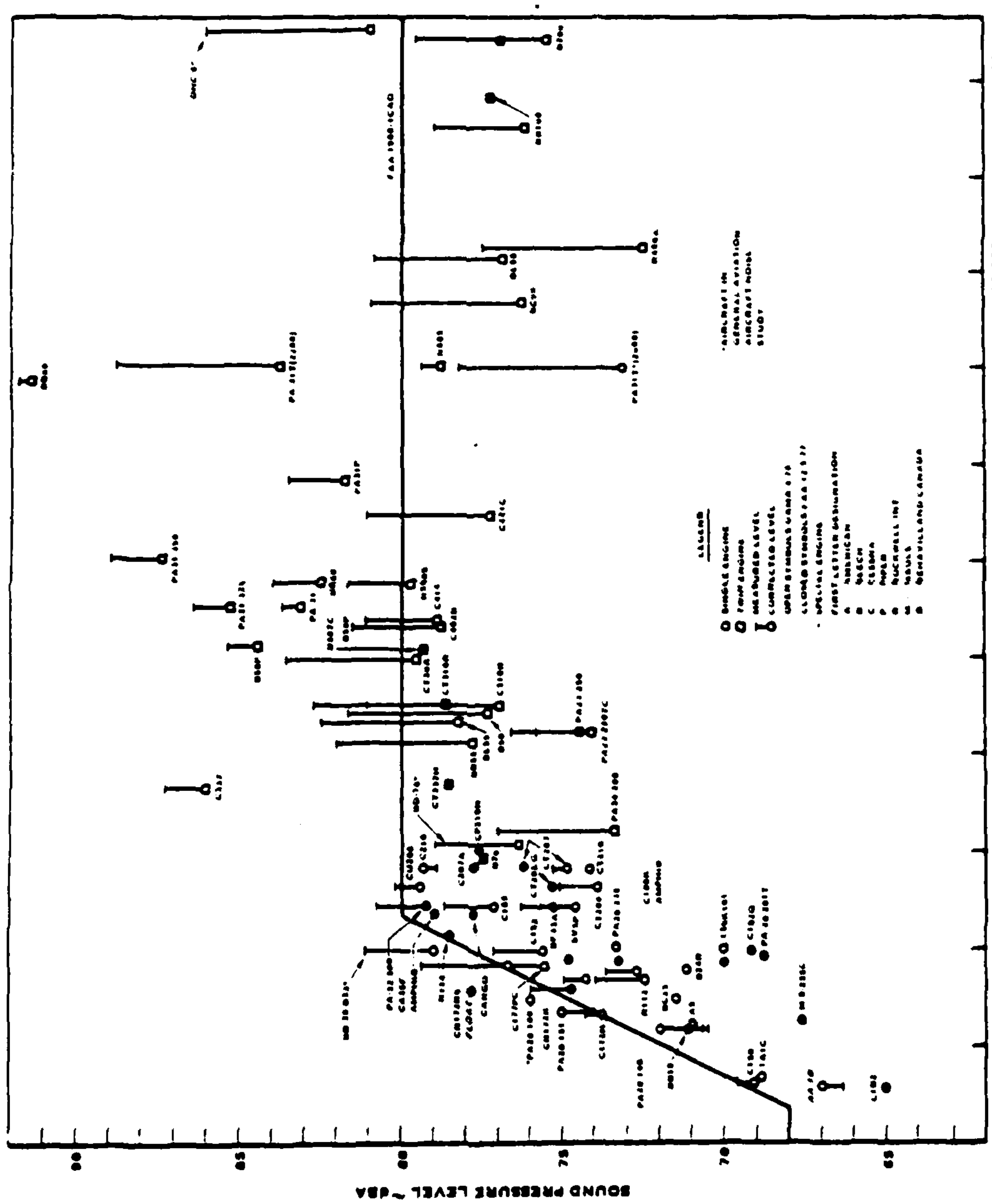


FIGURE 1. GENERAL AVIATION AIRCRAFT NOISE LEVELS

DISCUSSION

Evaluation of Noise Prediction Method

The noise prediction method used in the study is discussed in Appendix A. In order to confirm the accuracy of the method, the predicted A-weighted overall noise level and noise spectra were compared with propeller noise measurements for two candidate single engine aircraft, a light twin aircraft, and a heavy twin aircraft considered in the study. Table I summarizes the comparison between the measured and calculated A-weighted overall noise levels.

As seen from Table I, the noise prediction method agreement with measured data varies from a 2.5 dBA under prediction of the average noise level to a 3.9 dBA over prediction. For the Debonair, the single engine aircraft used in subsequent phases of the study and for the Duchess, Table I shows that the noise prediction method is in good agreement with data on an A-weighted overall basis. The noise prediction method over predicts the A-weighted overall noise level for the heavy twin, Twin Otter, aircraft. However, since the objective of the study is to define a delta change in overall noise level, the tendency to over predict is considered acceptable.

On a 1/3 octave band spectrum basis, the noise prediction method tends to match or over predict the noise level for the blade passage frequency. For the reference cases, the noise prediction method also tends to match or over predict the 2X blade passage frequency noise level. Agreement for the higher blade passage tones shows more scatter but is generally with ± 3 dB. The noise prediction method did not correctly predict broad band noise levels with the general tendency being to under predict except in the case of the Debonair. Comparison of the calculated versus measured 1/3 octave band spectra for the cases tabulated in Table I are shown in Figures 2 - 11.

Generally, the noise prediction method shows reasonable agreement with measured data for the overall noise level for the reference aircraft. The prediction method also shows reasonable agreement with measured propeller tone levels. However, agreement between calculated and measured broad band noise levels is not as good. The disagreement in broad band noise prediction is not considered significant as the overall noise level is dominated by the propeller tones which are generally well predicted. The comparison has also assumed that the flyover noise for the reference aircraft was dominated by the propeller noise, i.e. engine and airframe noise are not significant. Apparently, this is a valid assumption for the aircraft being considered. Based on the comparisons shown, it was concluded that the noise prediction method was accurate enough for the parametric studies described in the succeeding sections of this report.

TABLE I

PROPELLER CHARACTERISTICS SUMMARY

AIRCRAFT	SHP	DIA. FT	SHP/D^2	NO. BLADES	TIP MACH #	FLIGHT MACH #	TIP RELATIVE MACH #	dBA MEAS.	dBA CALC.
Piper PA28-20 Arrow II	200	6.0	5.55	2	0.734	0.232	0.770	69.5 - 75.0	70.0
Beechcraft 35-B33 Debonair	218	7.03	4.41	2	0.861	0.276	0.904	81.0	81.0
Beechcraft 76 Duchess	165	6.33	4.12	2	0.801	0.280	0.847	77.0 - 80.5	80.1
DeHavilland DHC6 Twin Otter	274	8.5	3.79	3	0.790	0.118	0.799	83.0	85.2
DeHavilland DHC6 Twin Otter	307	8.5	4.25	3	0.856	0.118	0.864	92.5	96.4

NOTE: Twin Otter cases were calculated and measured at 200 ft. and reduced by 14 dB(A) to correct to 1000 ft. distance, the same distance used for the other cases.

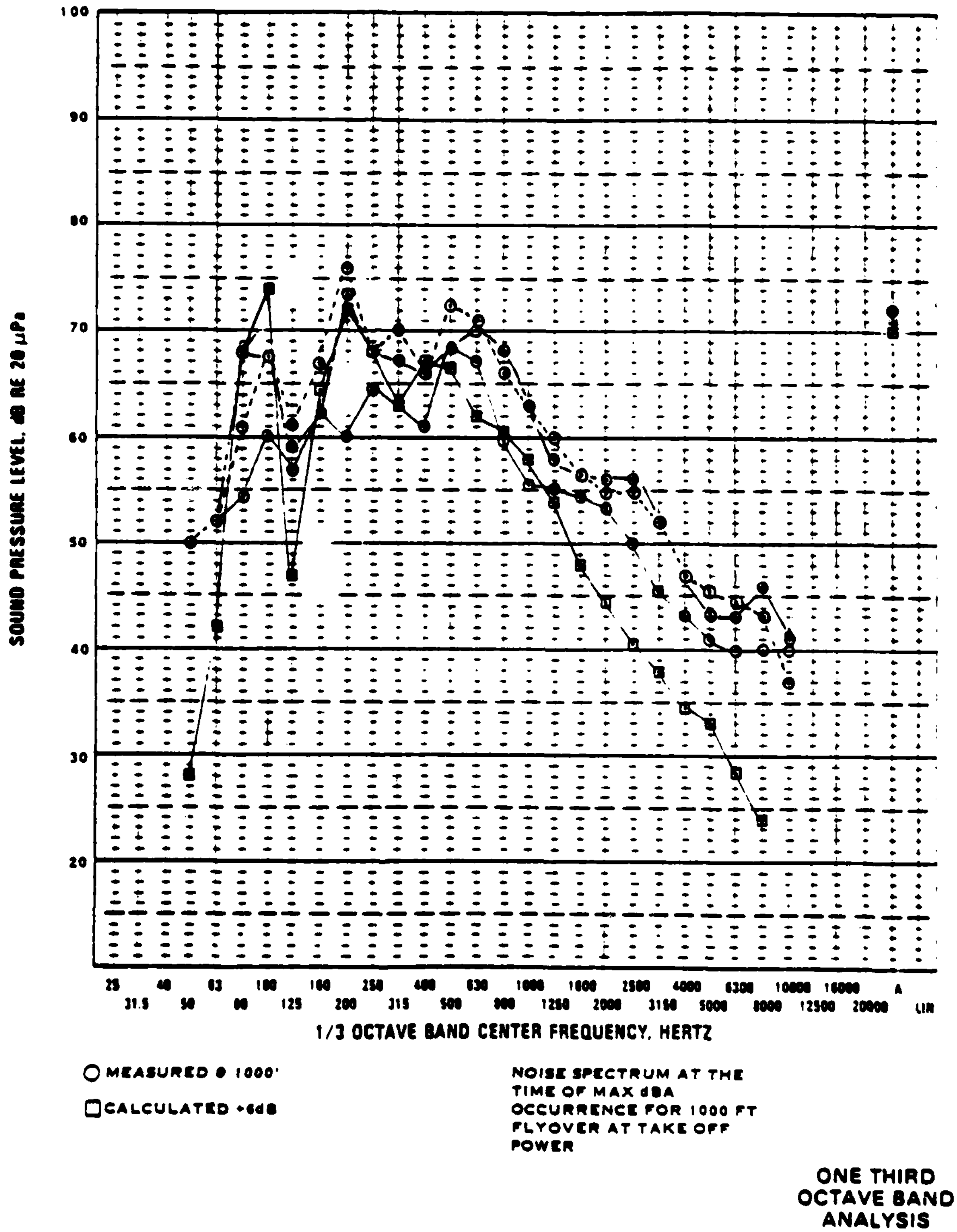
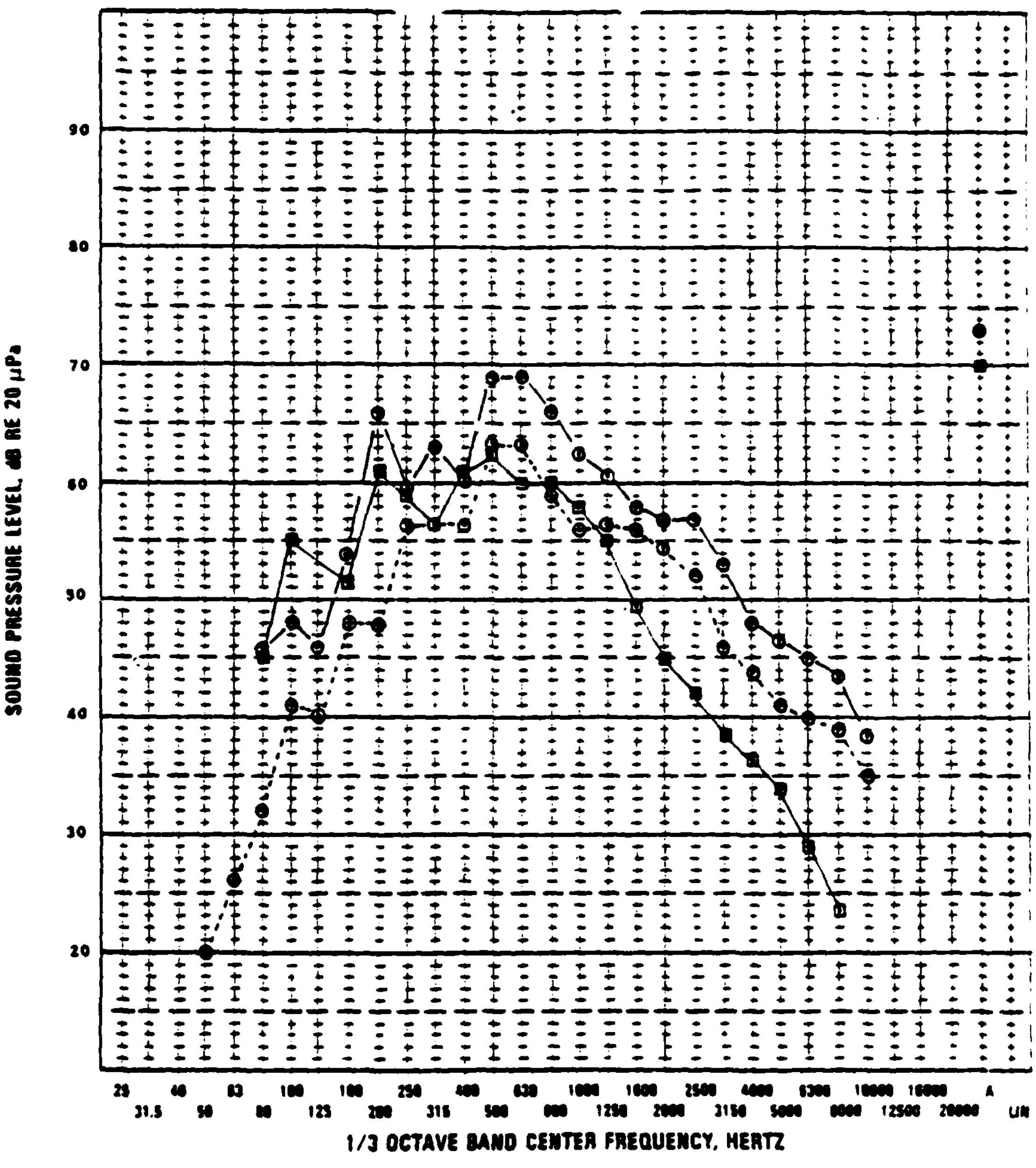


FIGURE 2. PIPER PA28-20 ARROW II FLYOVER NOISE



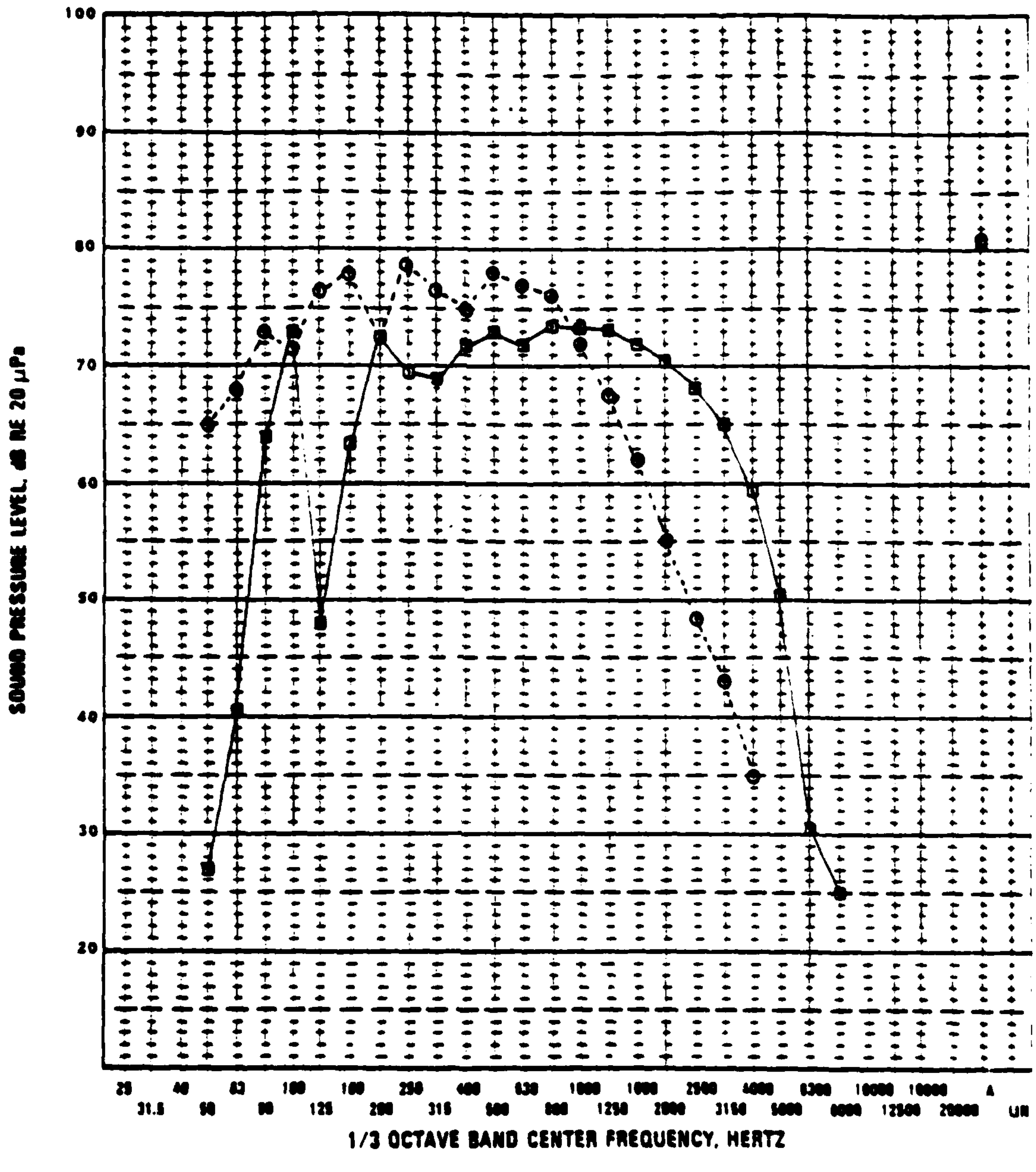
○ MEASURED @ 1000 FEET

□ CALCULATED +6 dBA

A-WEIGHTED SPECTRUM AT THE TIME OF MAX dBA OCCURRENCE FOR 1000 FT FLYOVER AT TAKE OFF POWER

ONE THIRD OCTAVE BAND ANALYSIS

FIGURE 3. PIPER PA28-20 ARROW II FLYOVER NOISE

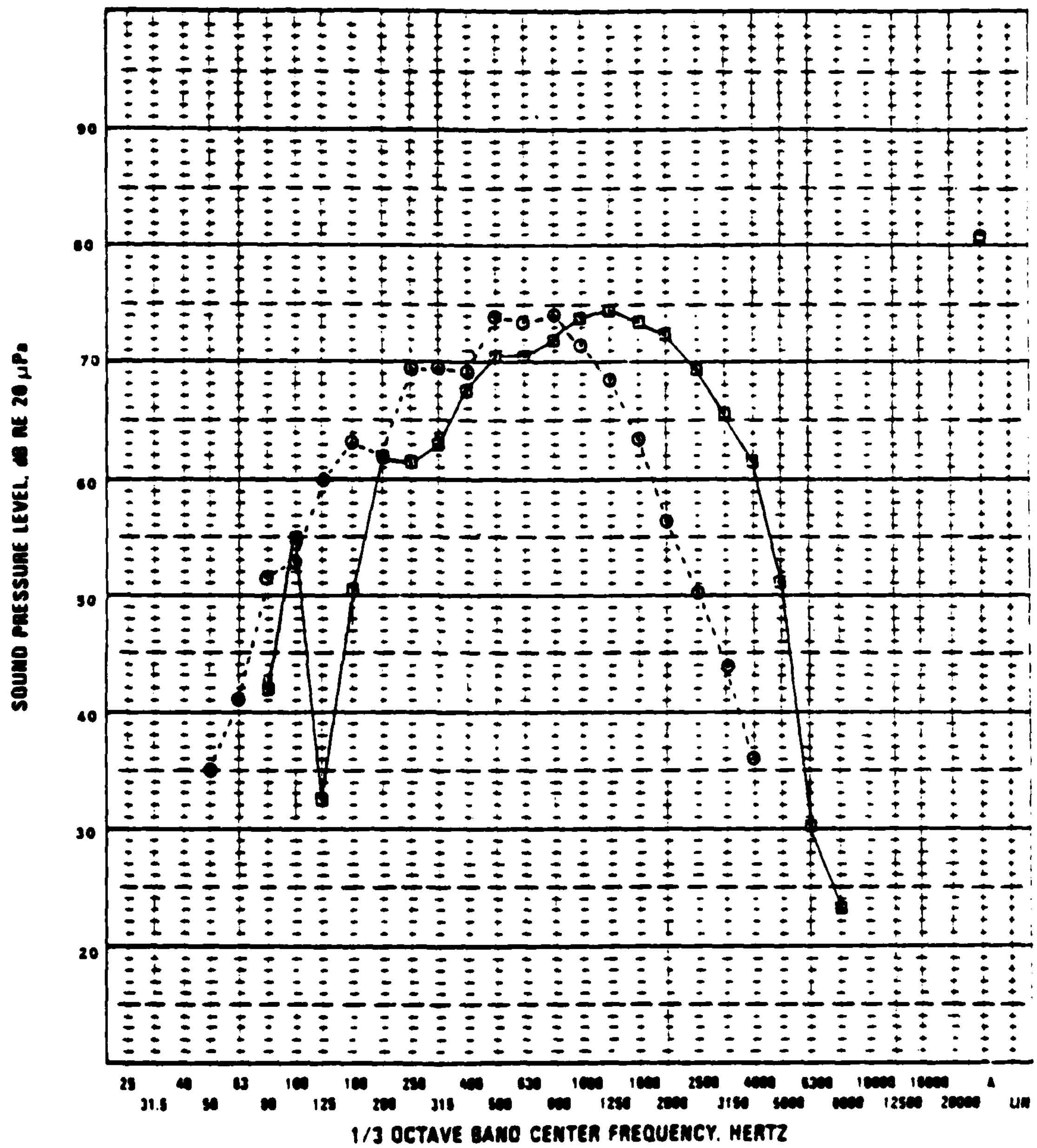


O – MEASURED @ 1000 FT
□ – CALCULATED + 6 dB

NOISE SPECTRUM AT THE TIME OF
MAX dBA OCCURRENCE FOR 1000 FT
FLYOVER AT TAKE OFF POWER

ONE THIRD OCTAVE BAND ANALYSIS

FIGURE 4. BEECHCRAFT DEBONAIR 35-B33 FLYOVER NOISE



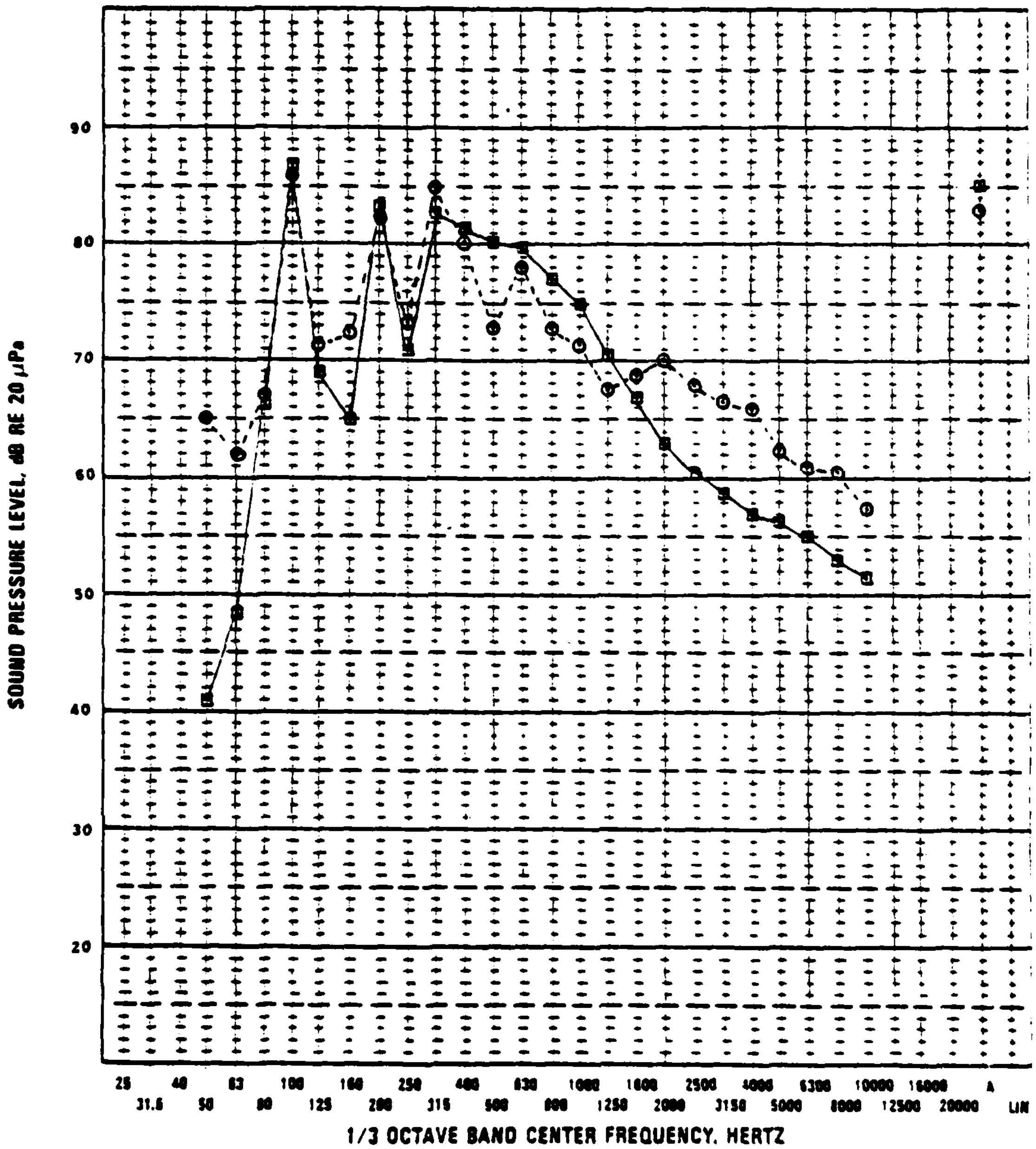
○ MEASURED @ 1000 FT

□ CALCULATED +6dBA

A-WEIGHTED SPECTRUM AT THE TIME OF MAX dBA OCCURRENCE FOR 1000 FT FLYOVER AT TAKE-OFF POWER

ONE THIRD OCTAVE BAND ANALYSIS

FIGURE 5. BEECHCRAFT DEBONAIR 35-B33 FLYOVER NOISE



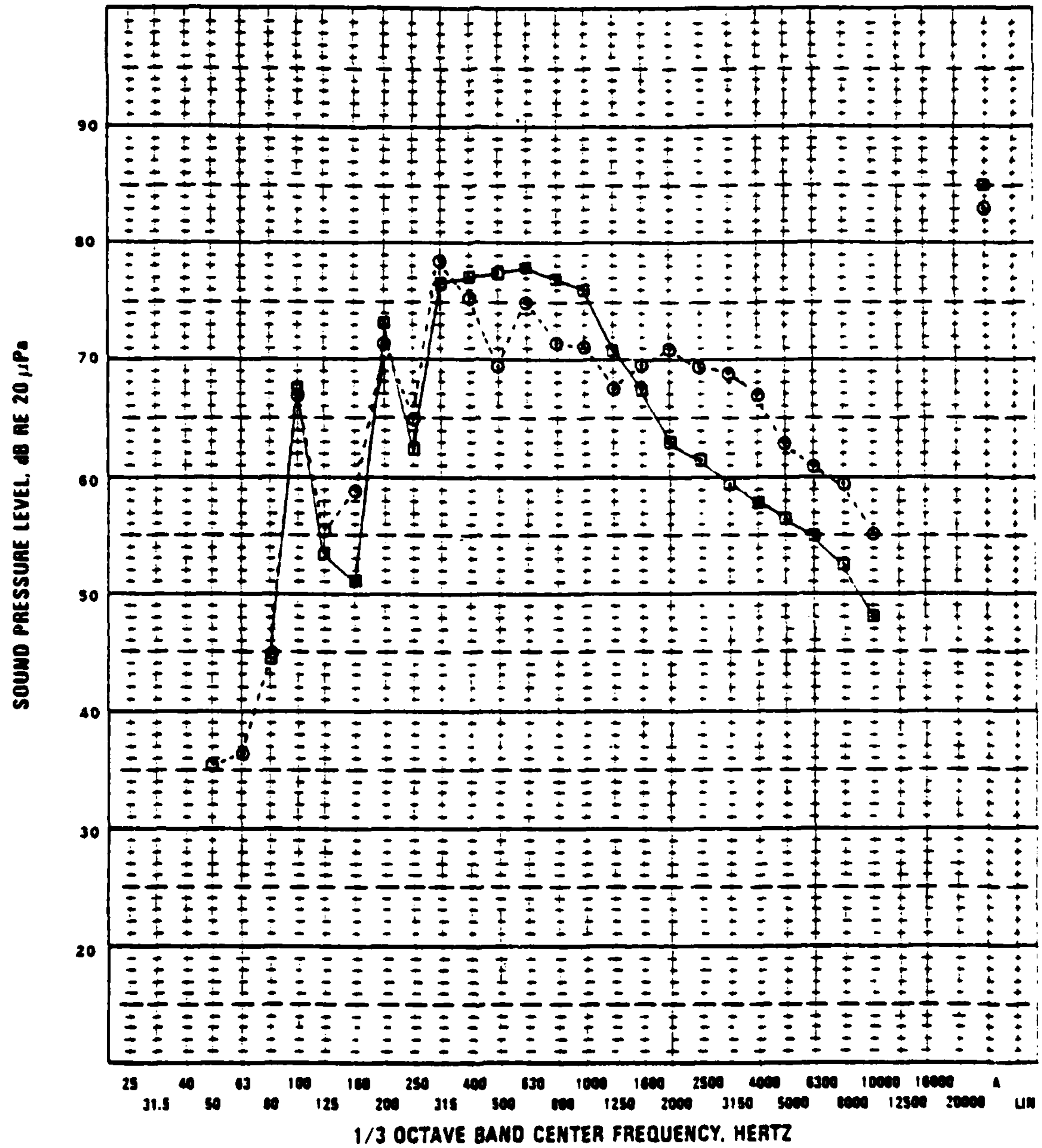
○ MEASURED @ 200 FT

□ CALCULATED +6 dB

NOISE SPECTRUM AT TIME OF MAX
dBA OCCURRENCE FOR 200 FT
1 ENGINE AT 90% RPM
1.2M MICROPHONE HEIGHT

ONE THIRD
OCTAVE BAND
ANALYSIS

FIGURE 6. DHC-6 TWIN OTTER FLYOVER NOISE



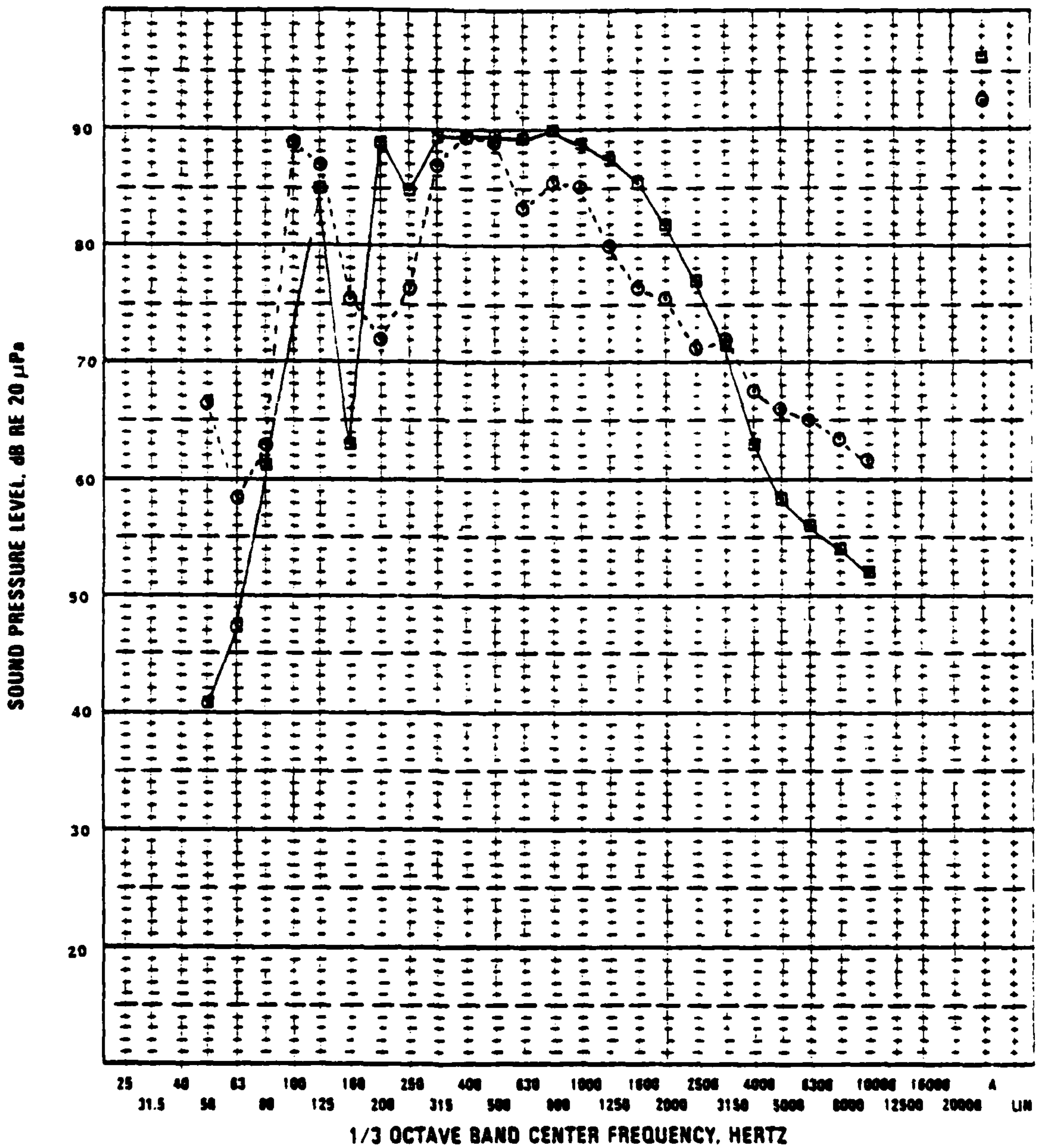
○ MEASURED @ 200 FT

□ CALCULATED +6dBA

A-WEIGHTED SPECTRUM AT THE TIME OF MAX dBA OCCURRENCE FOR 200 FT 1 ENGINE AT 90% RPM 1.2 M MICROPHONE HEIGHT

ONE THIRD OCTAVE BAND ANALYSIS

FIGURE 7. DHC-6 TWIN OTTER FLYOVER NOISE



○ MEASURED @ 200 FT

□ CALCULATED + 6dB

NOISE SPECTRUM AT THE TIME OF MAX dBA OCCURRENCE FOR 200 FT FLYOVER 1 ENGINE AT 97.5% RPM
1.2 M MICROPHONE HEIGHT

ONE THIRD OCTAVE BAND ANALYSIS

FIGURE 8. DHC-6 TWIN OTTER FLYOVER NOISE

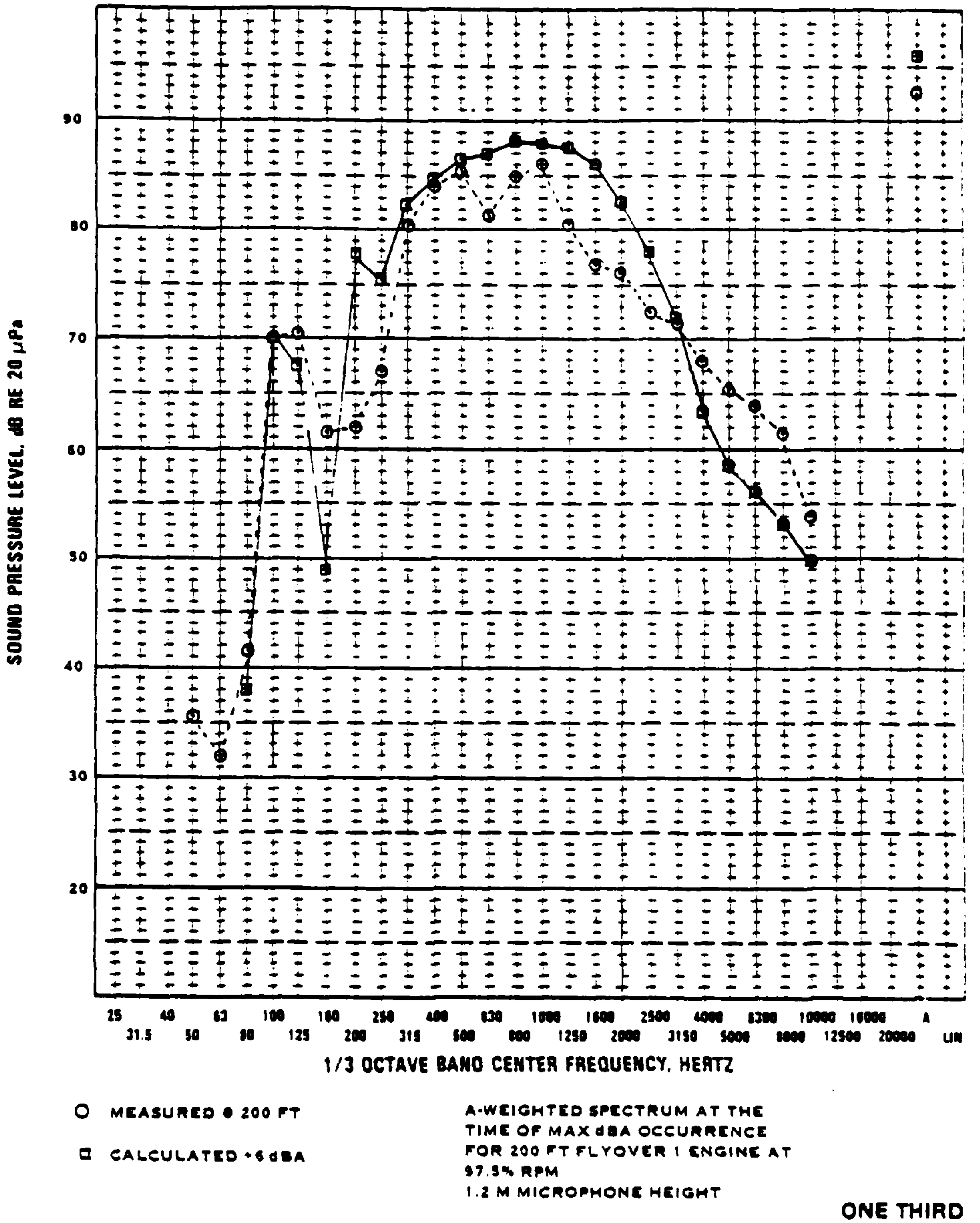
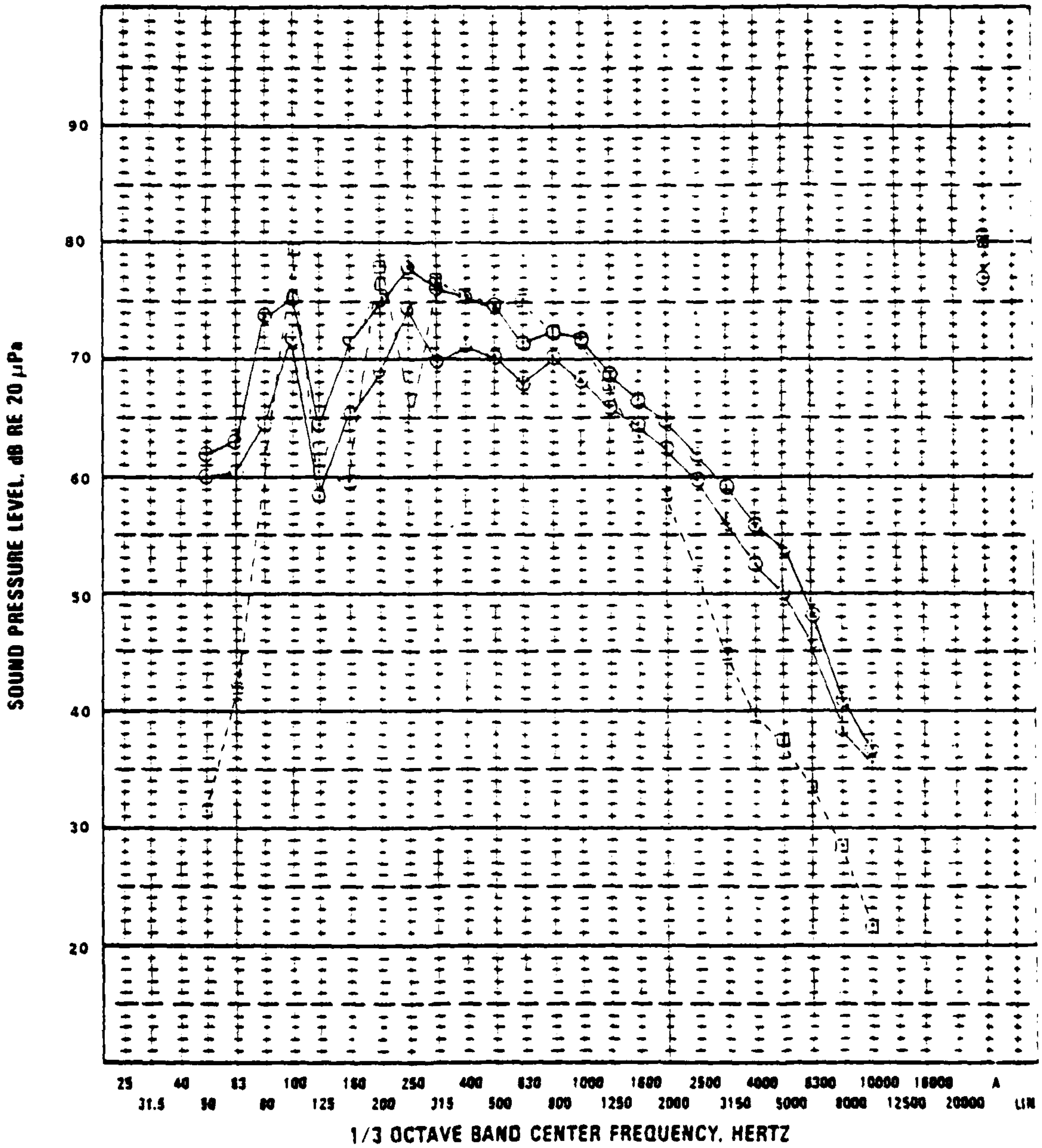


FIGURE 9. DHC-6 TWIN OTTER FLYOVER NOISE



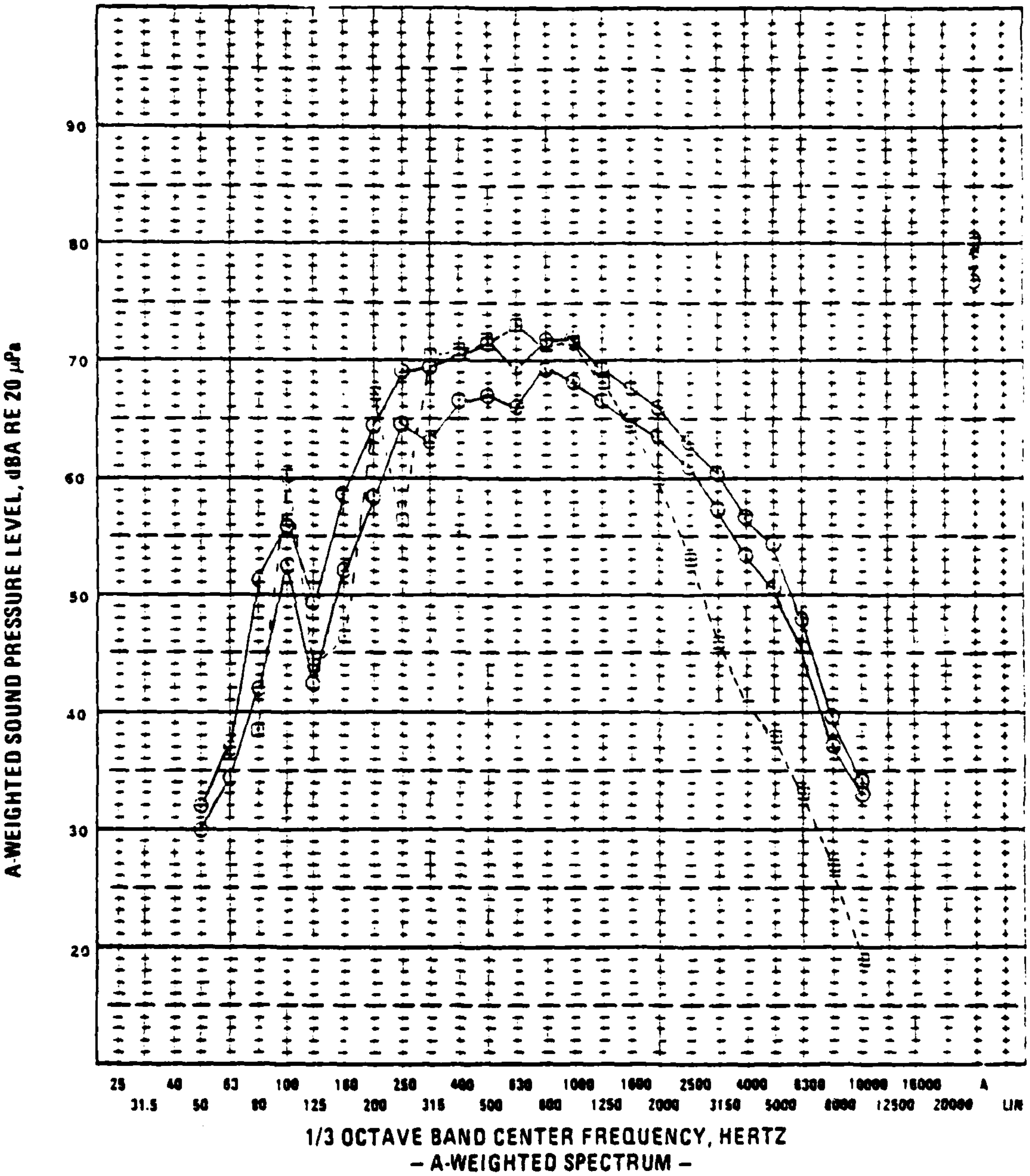
○ TEST DATA (MAX-MIN RANGE PLOTTED)
BLADE PASSAGE FREQUENCY ~90 HZ

□ CALCULATION +6 dB

BPF = 90 HZ

ONE THIRD OCTAVE BAND ANALYSIS

FIGURE 10. BEECH DUCHESS FLYOVER NOISE



○ TEST DATA (MAX-MIN RANGE PLOTTED)
BLADE PASSAGE FREQUENCY ~90 HZ

□ CALCULATION +6 dB

BPF = 90 HZ

FIGURE 11. BEECH DUCHESS FLYOVER NOISE

ONE THIRD
OCTAVE BAND
ANALYSIS

DISCUSSION

Study of Single Engine Aircraft

The noise components calculated for the existing propeller on the Beech Debonair as shown in Figure 12 indicated that the noise associated with the thickness (and volume) of the blade was the major problem. It can be seen in Figure 12 that the mid frequencies which are most important in A weighted levels are dominated by thickness noise. Also, experience has shown that the outer quarter of the blade produces most of the noise. Therefore, the primary emphasis in the Debonair blade study was on reduction of thickness noise of the blade tips. Noise reduction modifications included: (1) optimizing tip shape, (2) reducing tip thickness, (3) optimizing performance and increasing number of blades to allow a reduction in diameter (and therefore tip speed), and (4) incorporating tip modifications.

Tip shape (planform) has been reported in the past to have a significant effect on propeller noise. However, there have not been any recent studies of the effect of tip shape which use modern noise prediction methodology capable of establishing the influence of small changes in tip configuration. Therefore, in the present study, noise produced by the thick tip configuration as shown in Figure 13 was predicted and compared with the noise of the existing McCauley (modified rectangular) propeller. The blade definitions for the tip shapes of Figure 13 are presented in Figure 14. Note that the thickness and twist distribution of the blades was held constant for this comparison.

Figure 15 shows the difference in A weighted levels and 1/3 octave band spectra for the different tip shapes relative to the existing McCauley designs. It can be seen that the elliptical tip blade is lowest in noise level relative to the round and rectangular tip blades. The difference in propeller noise level between the rectangular and elliptical tip blades was 3.2 dBA. Comparison of the noise components for the elliptical and rectangular tip blades in Figure 16 shows that the improvement in noise level for the elliptical tip propeller was primarily the result of a reduction in the thickness noise. There was also a substantial reduction in quadrupole noise for the elliptical tip propeller. However, the level of the quadrupole noise did not have any significant impact on the overall noise level. The majority of the noise reduction was caused by the reduction in thickness noise resulting from the chord reduction in the tip of the elliptical tip propeller.

Also, it can be seen in Figure 15 that the noise of the McCauley propeller exceeds the noise of other designs. This is due to the higher thickness of the McCauley design which is shown in the upper curves of Figure 14.

Since the tip region of the propeller is the important source of noise, the reduction of lift coefficient, C_L, or aerodynamic loading in this region was investigated as a noise reduction concept. Lift coefficient was lowered by modifying the radial twist distribution of the propeller. Two different C_L distributions were evaluated for the three tip shapes discussed above. Twist distribution #2 produces a tip C_L level that is consistent with normal propeller design practice while twist distribution #1 produces a C_L near zero at the propeller tip. Twist distribution #1 was expected to have a lower level of loading noise than twist #2 and consequently, lower overall propeller noise. The C_L and twist distributions used in the study are compared with those of the McCauley propeller in Figure 17. It can be seen that the loading distribution produced by twist #2 is closest to that of the McCauley propeller.

Propeller noise was calculated for both twist distributions for the rectangular, round and elliptical tip shape propellers. One third octave band spectra were shown earlier for twist #2 in Figure 15. Figure 18 shows the one third octave band spectra for twist #1. Comparison of Figures 15 and 18 shows that the twist/C_L distribution has no influence on the relative effect of tip shape on noise. The elliptical tip has the lowest noise level regardless of C_L level. Comparison of identical planforms indicates that reducing the C_L level in the tip region produces a small noise benefit. Propeller noise levels are reduced in the order of 0.5 to 1.0 dBA by the C_L reduction used in this study.

From Figure 19, it can be seen that reduction of the tip C_L produces a reduction in the steady loading noise. However, the overall noise level is dominated by the thickness noise, which is unchanged.

It has been observed earlier in this report that the McCauley propeller currently on the Beechcraft Debonair is thickness noise dominated. The best tip shape for a replacement propeller was found to be an elliptical tip with a reduced chord in the tip region relative to the McCauley propeller. Thickness noise can be reduced through either a reduction of blade chord or blade thickness in the propeller tip region or some combination of both. To evaluate the effect of blade thickness the noise levels were calculated for an elliptical tip propeller for two levels of thickness to chord ratio. A reduction in tip thickness (h/b of 50-100% from 80 to 100% diameter produced a reduction in propeller noise level of 2.5 dBA. Figure 20 compares the one third octave band spectra of the two different thickness elliptical tip blades with the spectrum of the McCauley propeller. A reduction in mid-frequency noise is shown for the thin tip. A comparison of the noise components for the three propeller configurations is shown in Figure 21. This comparison confirms that the reduction in thickness noise at mid frequencies is responsible for the overall noise reduction. The geometry of the McCauley propeller is compared with that of the two elliptical tip propellers in Figure 22. It can be seen that the elliptical tip configuration significantly reduces tip chord relative to the McCauley blade and that the thin tip blade is also significantly thinner than the McCauley blade.

One of the requirements for the study reported here is that the replacement propellers should not noticeably degrade the performance of the aircraft under study. Two conditions were selected as being representative of critical performance conditions for the study: (1) a takeoff climb condition, and (2) a high speed 1,000 foot flyover typical of certification. The modifications described previously were all of the kind that maintained the original aircraft performance. However, one of the standard methods for reducing propeller noise has been the reduction of diameter and therefore the reduction in tip speed for a given RPM. This, of course, normally reduces performance unless blades are added to the propeller. Figure 23 shows how the 2 blade elliptical tip propeller performed in takeoff and flyover at various diameters. The reference existing performance requirement shown at the right of each curve was obtained by calculation using the McCauley blade definition which has been discussed earlier. Of course, as propeller diameter is reduced, the slipstream velocity increases for a given thrust. Therefore, the drag associated with this higher velocity air passing over the aircraft components downstream of the propeller increases the thrust required for a given aircraft performance. Appendix E describes the method used to establish the increase in thrust required at smaller diameters.

Figure 23 shows one of the surprising results of the study. Here it is shown that the elliptical tip 2 blade replacement propeller produces greater thrust at takeoff and flyover conditions than the existing McCauley propeller. This is believed to be due to the better performance of the NACA Series 16 airfoils used in the replacement design relative to performance of the RAF 6 airfoils in the McCauley design. The literature indicates that the improved airfoil performance is caused by the laminar flow design of the NACA Series 16 as compared with the turbulent flow design of the RAF 6. Also, it appears that the planform, twist distribution, and airfoil thickness of the replacement propeller contribute to its performance benefit. With performance that exceeds the requirement at the 7 ft reference diameter it becomes feasible to reduce diameter and therefore reduce noise. Using the performance methodology described in Appendix B, the performance with diameter reduction shown in Figure 23 was established. It can be seen that reducing the diameter by 0.5 ft is feasible while still exceeding the thrust requirement curve both at the takeoff and flyover conditions.

Addition of another blade to the Debonair replacement propeller permitted an additional diameter reduction of 3" as shown in Figure 24. The noise reduction for the replacement 2 and 3 blade propellers is discussed later. Based on the above study, performance optimization of the propeller was concluded to be a critical step in the design of a low noise propeller. The best performing airfoils available should be utilized and propeller performance should be thoroughly optimized to produce the minimum diameter design that satisfies the performance requirements.

Figure 23 showed that the takeoff performance was the critical design point for the 2 blade propeller. The flyover performance requirement could be achieved in a 6.25 ft diameter propeller but the takeoff performance required a 6.5 ft diameter propeller. If takeoff performance could in some way be enhanced without degrading flyover performance, then the propeller diameter might be reduced. Also, it is possible that a tip device could be added that causes a cancellation of thickness and loading noise at some frequencies.

It is known that installing a shroud around a propeller enhances its takeoff performance. However, there is a weight penalty for such a shroud. As an alternative, winglets, end plates, or bent tips might be used to simulate the shroud effect in the local area around the blade tips. These devices are believed to improve performance by reduction of the circulation of air over the propeller tip. Calculations were made in this study where the performance of tip modifications was approximated by assuming that they performed like a short chord shroud. This study showed that the performance losses of the shroud balanced the performance gains. However, a more precise analysis might show that carefully tailored tip modifications provide useful performance gains. Such an analysis was beyond the scope of this study. Also, the structural aspects of adding tip devices must be assessed.

It is known that bent tips are being considered for installation on several aircraft at the present time. Reports indiate, however, that the existing bent tip configuration provides no clear cut performance or noise reduction benefit. Therefore, it appears that the potential of such devices will not be realized until extensive analytical and experimental work is conducted.

Blade sweep was also considered as a noise reduction concept. Noise reduction accomplished by this modification is due to phase cancellation of noise generated at various spanwise locations on the blade. This is discussed in Appendix A. It was found that a substantial amount of tip sweep was required to achieve worthwhile noise reductions. For example, the blade shown in Figure 25 has a 52° tip sweep and shows a 5.5 dBA reduction relative to the same blade without sweep. As seen in Figure 26 the noise reduction for the swept blade occurs at frequencies above 250 Hz. Figure 27 shows that this reduction is a result of reduction in thickness, steady loading, and quadrupole noise. It was concluded that the level of reduction achieved by sweep for the Debonair propeller could probably be achieved with less cost and weight impact by alternate noise reduction methods. Further study which includes structural evaluation of the designs appears warranted if noise reductions are required which are greater than can be achieved with the alternate approaches summarized below. Of course, such reductions would require engine noise reductions as discussed below.

Three noise reduction goals were established for the study: (1) the maximum noise reduction that can be achieved before engine noise suppression becomes necessary, (2) the noise reduction that can be achieved without a weight or cost penalty, and (3) the maximum noise reduction that can be achieved without a weight or cost penalty, and (3) the maximum noise reduction that can be achieved without an aircraft performance penalty. In achieving the first goal, it was assumed for purposes of this study that engine noise suppression is required when propeller noise is within 2 dBA of the engine noise level. Although the swept blades are included in Figures 28 and 29, the lack of cost prediction and the requirement to further study the structural design of such blades prevented their selection as fulfilling any of the goals. Where two configurations in Figures 28 and 29 are within $\pm$ .5 dBA the configuration with the lowest weight and cost was selected as having achieved the goal.

The first goal, i.e. the maximum noise reduction that can be achieved before engine noise suppression becomes necessary, and the second goal, i.e., the noise reduction that can be achieved without a weight or cost penalty; were achieved with configuration 15 of Figure 28. This propeller is a 2 blade, thin elliptical tip configuration with a smaller diameter than the original McCauley blade. This propeller showed a propeller noise reduction of 11.1 dBA relative to the McCauley design with a 20% weight reduction and 22% cost reduction. As shown in Figure 29, the combined propeller and engine noise reduction for this configuration, assuming an unmuffled engine exhaust is 8.3 dBA. The most important noise reduction change for this design is the use of a thin elliptical tip. In addition, the 2% better performance of the NACA Series 16 airfoils relative to that of the RAF-6 airfoils used in the McCauley design permitted a 6 inch reduction in diameter and, therefore, a reduction in tip speed. This difference in airfoil performance is supported by airfoil data from the literature. The Series 16 airfoil is a laminar flow design while the RAF-6 is a turbulent boundary layer design.

The propeller configuration noise reduction concepts investigated for the single engine Debonair are summarized in terms of configuration, noise reduction, weight, and cost for the Debonair are summarized in Figure 28. The configura tions have been ranked in increasing noise reduction from left to right. Configuration 1 at the left is the existing McCauley propeller.

Two-blade configurations 2 through 12 show varying degrees of noise reduction with no cost or weight penalties relative to the McCauley propeller. However, these configurations do not attain the degree of noise reduction given by Configuration 15 which also has two blades and all weigh and cost more than configuration 15. Configurations 13, 18, and 19 are swept configurations which are required for this structural design and cost study. Configuration 14 is a thick tip, three-bladed propeller which does not provide the level of noise reduction of configuration 15 because of the thicker airfoil sections. Configuration 14 also has a cost penalty. Configurations 16 and 17 are three-bladed propellers that provide larger noise reductions than configuration 15, but have associated weight and/or cost penalties. The 13.7 dBA reduction obtained with configuration 17 was the largest noise reduction for a straight blade propeller. Swept blade configurations 18 and 19 have thick and thin round tip blades. Configuration 19 shows a 2.7 dBA greater noise reduction than the best straight blade propellers (configuration 17) but requires structural design and cost studies to establish its feasibility as a quiet replacement propeller.

To evaluate the impact of propeller noise reduction on the overall aircraft flyover noise, the combined engine and propeller noise level was calculated using Reference 1 to estimate the engine noise. The combined propeller and engine noise levels for the configurations of Figure 28 are shown in Figure 29. It can be seen in Figure 28 that the best noise reduction for the propeller alone is about 16 dBA for configuration 19, but because of the engine noise contribution, Figure 29 shows that the noise reduction for the aircraft would be about 10 dBA.

The third goal, i.e., the maximum noise reduction that can be achieved without performance penalty, was achieved with configuration 17 of Figure 28. The propeller is a 3 blade thin elliptical tip configuration with a smaller diameter than that used in configuration 15. This propeller showed a propeller noise reduction of 13.7 dBA reduction relative to the McCauley design with a 3% weight reduction, but a 24% cost penalty. As shown in Figure 29, the combined propeller and engine noise reduction for this configuration, assuming an unmuffled engine exhaust, is 9.4 dBA. It can be seen that further reductions in propeller noise are possible with swept tip designs such as configuration 19. However, such designs require structural design and cost studies which were beyond the scope of the present contract. If additional reductions beyond goal 3 are of interest, then engine muffling should be considered and further study of swept blades should be conducted.

Important geometry and aerodynamic parameters of configurations 1 through 19 are summarized in Table II. Lift coefficient, b/D and h/b are listed at the 75% radius and blade tip stations for the 19 propeller configurations to indicate levels relative to the McCauley propeller.

References

1. Magliozzi, B., "Small Aircraft Propeller/Engine Noise Prediction," FAAW1-76-0357-1, November 20, 1975, Final Report.

TABLE II

SINGLE ENGINE DEBONAIR PROPELLER CONFIGURATIONS

CONFIGURATION	NO. OF BLADES	PROPELLER DIAMETER - FT	AIRFOIL SERIES	ACTIVITY FACTOR	b/D @ .75 r	b/D @ .99r	h/b @ .75 r	h/b @ TIP	C_{L_O} @ .75 r	C_{L_O} @ TIP	SWEEP ANGLE @ TIP-DEGREES	TIP HELICAL M_N	DESIGN C_{L_1}	TIP SHAPE
1	2	7.0	RAF-6	97.2	.071	.044	.068	.060	.268	.290	0°	.89	.508	NOMINAL
2	2	7.0	16	86.1	.058	.035	.067	.060	.429	.218	0°	.89	.508	ROUND
3	2	7.0	16	89.8	.070	.022	.067	.060	.365	.238	0°	.89	.508	ELLIPTICAL
4	2	7.0	16	95.7	.067	.047	.066	.027	.309	.067	0°	.89	.508	NOMINAL
5	2	7.0	16	89.0	.058	.053	.045	.027	.422	.144	0°	.89	.508	RECTANGULAR
6	2	7.0	16	86.1	.058	.035	.045	.027	.424	.208	0°	.89	.508	ROUND
7	2	7.0	16	89.0	.058	.053	.045	.027	.535	-.075	0°	.89	.508	RECTANGULAR
8	2	7.0	16	86.1	.058	.035	.045	.027	.535	-.098	0°	.89	.508	ROUND
9	2	7.0	16	89.8	.070	.022	.045	.027	.360	.225	0°	.89	.508	ELLIPTICAL
10	2	7.0	16	89.8	.070	.022	.045	.027	.445	-.205	0°	.89	.508	ELLIPTICAL
11	2	6.5	16	89.8	.070	.022	.067	.060	.482	.374	0°	.84	.500	ELLIPTICAL
12	2	6.5	16	95.7	.067	.047	.066	.027	.428	.168	0°	.84	.508	NOMINAL
13	2	7.0	16	86.1	.058	.035	.045	.027	.456	.169	52°	.89	.508	ROUND
14	3	6.25	16	89.8	.070	.022	.067	.060	.383	.297	0°	.81	.508	ELLIPTICAL
15	2	6.5	16	89.8	.070	.022	.045	.027	.480	.373	0°	.84	.508	ELLIPTICAL
16	3	6.25	16	95.7	.067	.047	.066	.027	.33	.120	0°	.81	.508	NOMINAL
17	3	6.25	16	89.8	.070	.022	.045	.027	.380	.293	0°	.81	.508	ELLIPTICAL
18	3	6.25	16	86.1	.058	.035	.067	.060	.458	.193	52°	.81	.508	ROUND
19	3	6.25	16	86.1	.058	.035	.045	.027	.473	.211	52°	.81	.508	ROUND

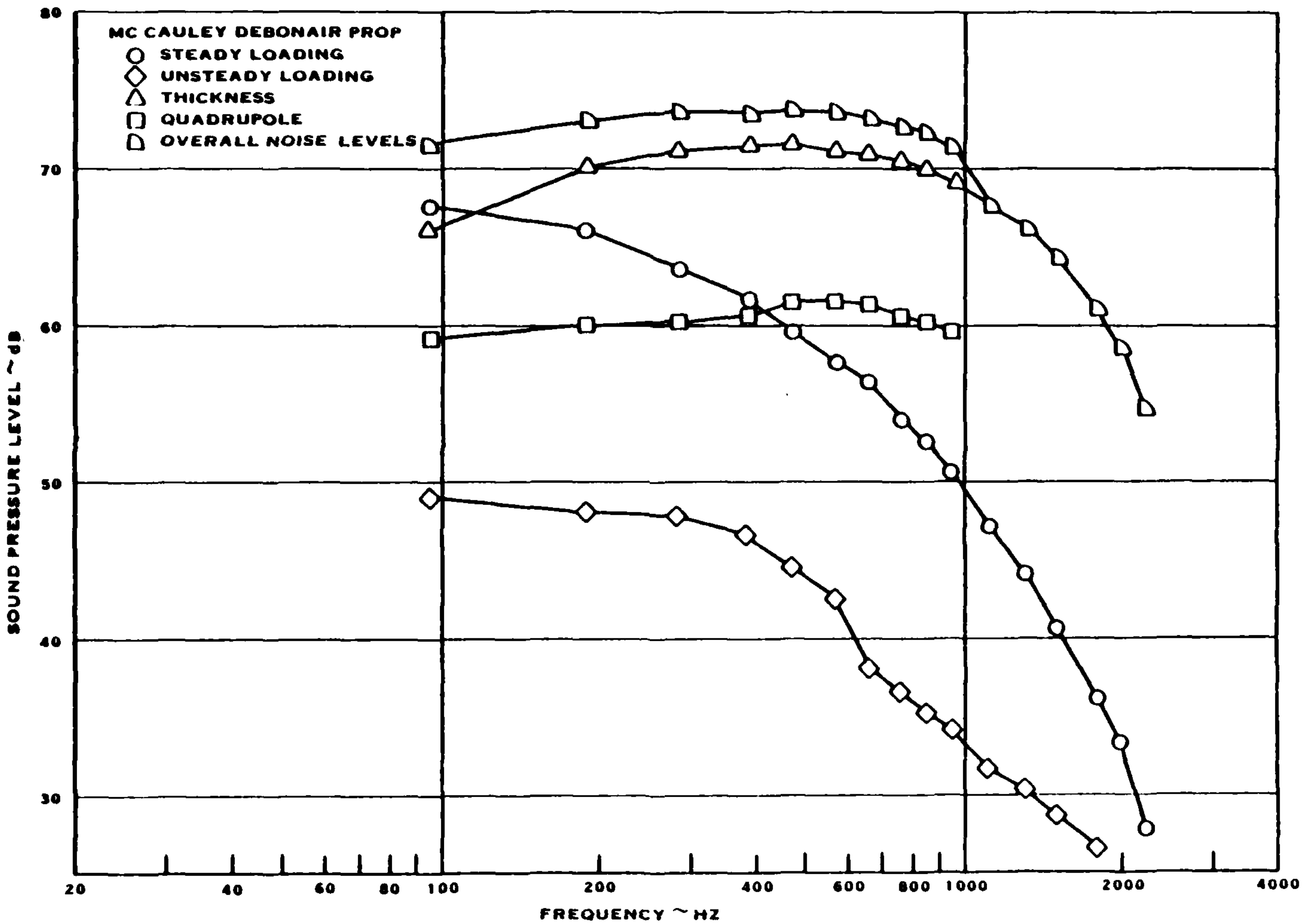


FIGURE 12. NOISE COMPONENTS FOR MC CAULEY PROPELLER

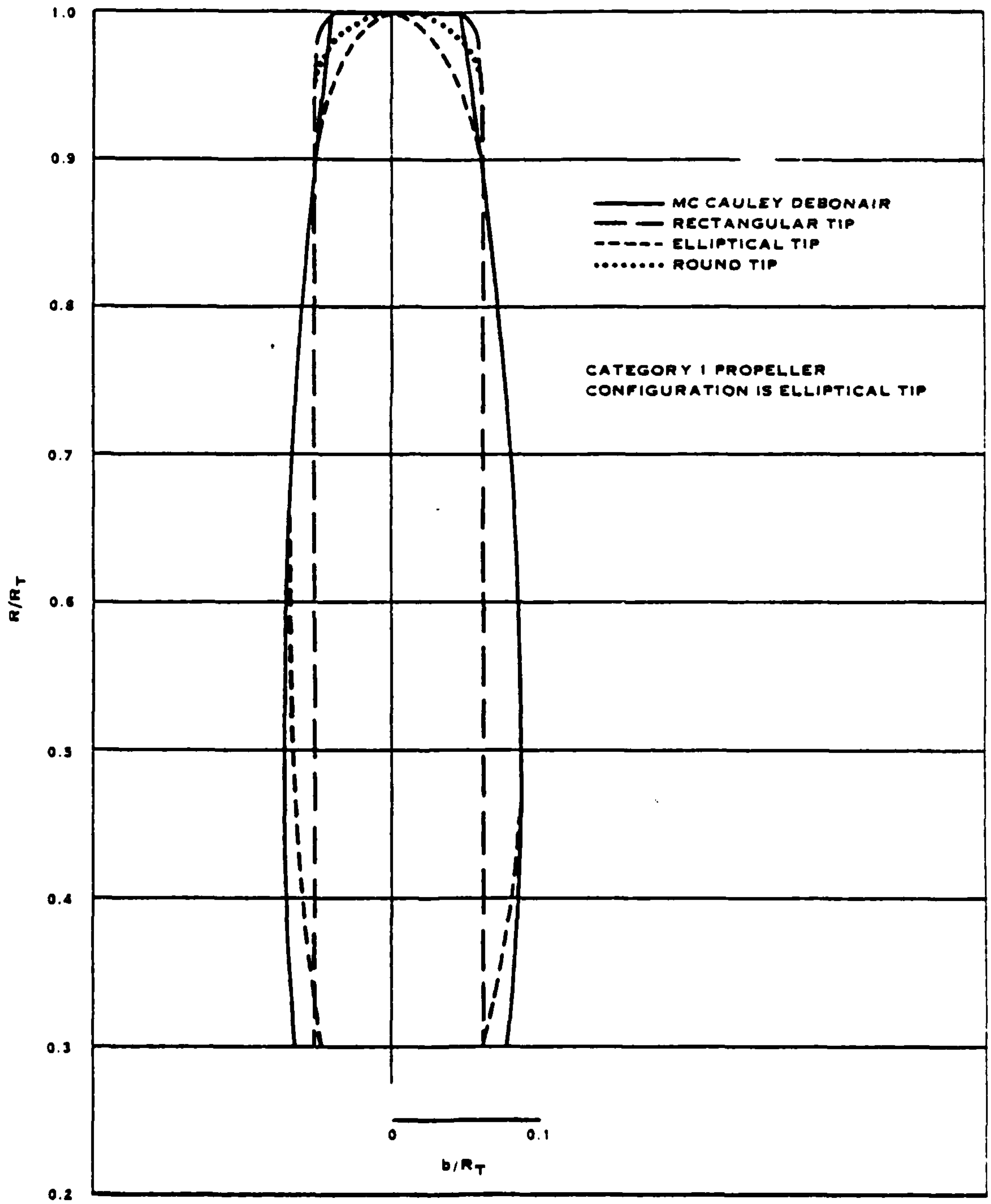


FIGURE 13. SINGLE ENGINE DEBONAIR PROPELLER PLANFORMS

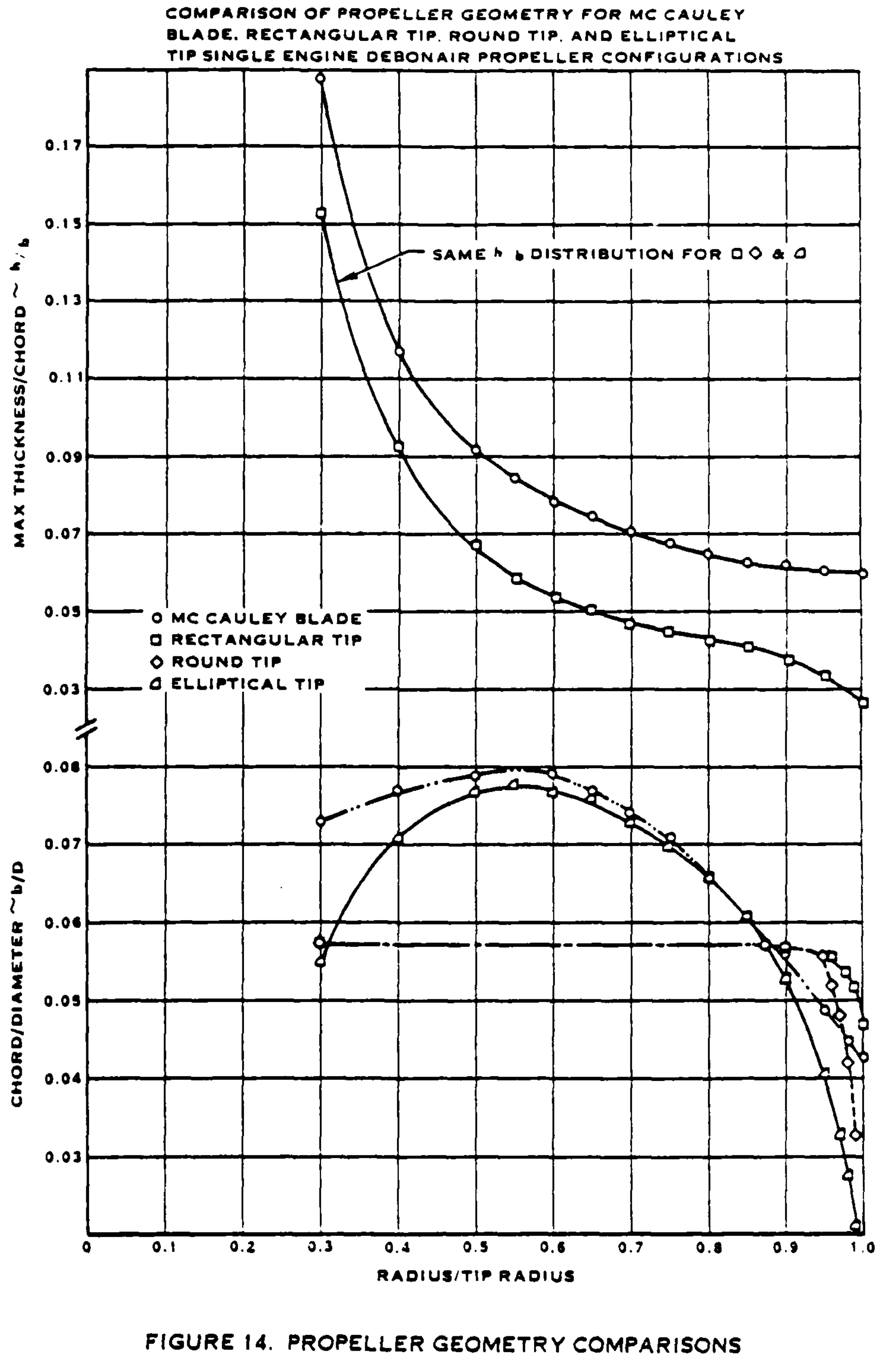
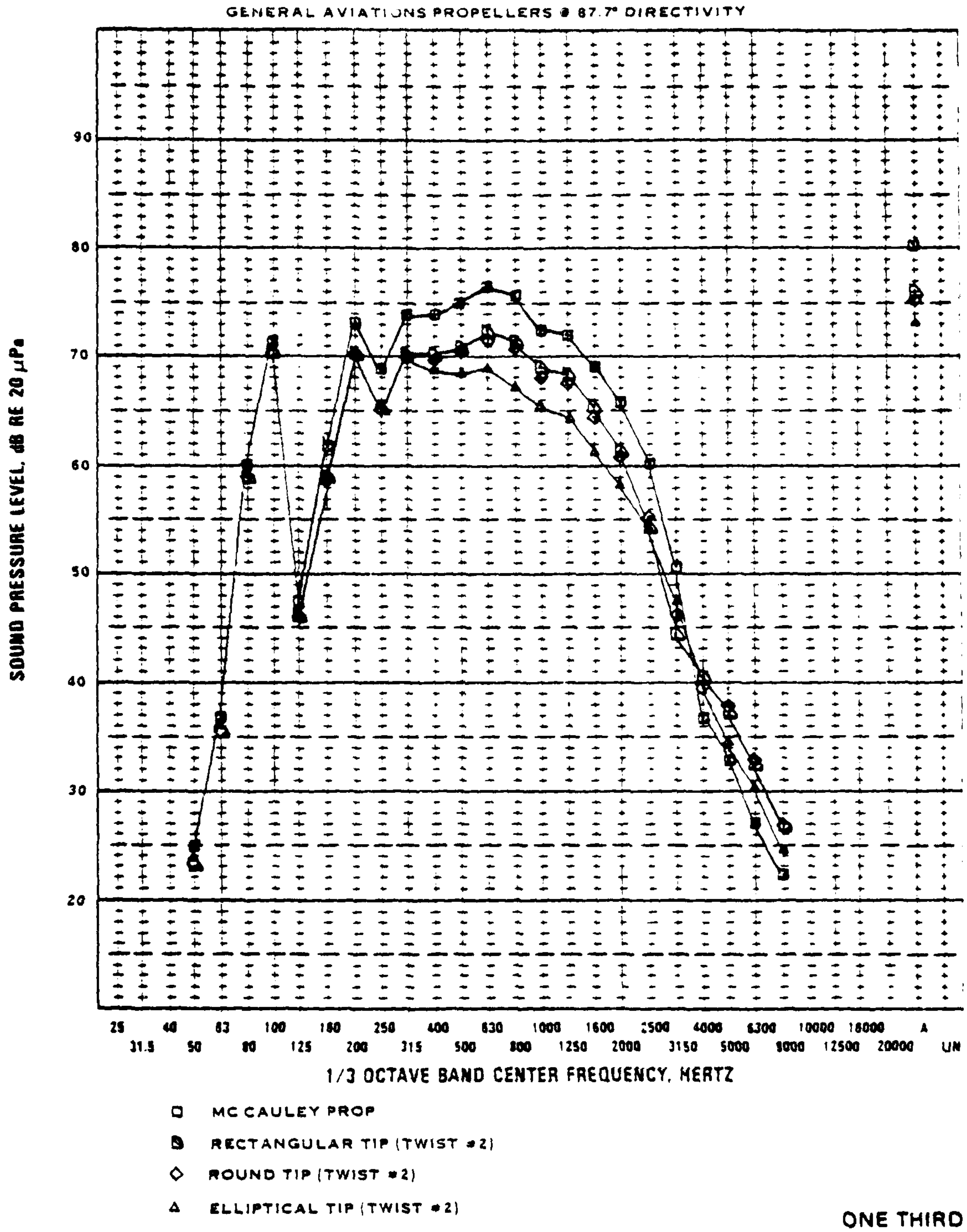


FIGURE 14. PROPELLER GEOMETRY COMPARISONS



ONE THIRD OCTAVE BAND ANALYSIS

FIGURE 15. EFFECT OF TIP SHAPE ON ONE THIRD OCTAVE BAND SPECTRA

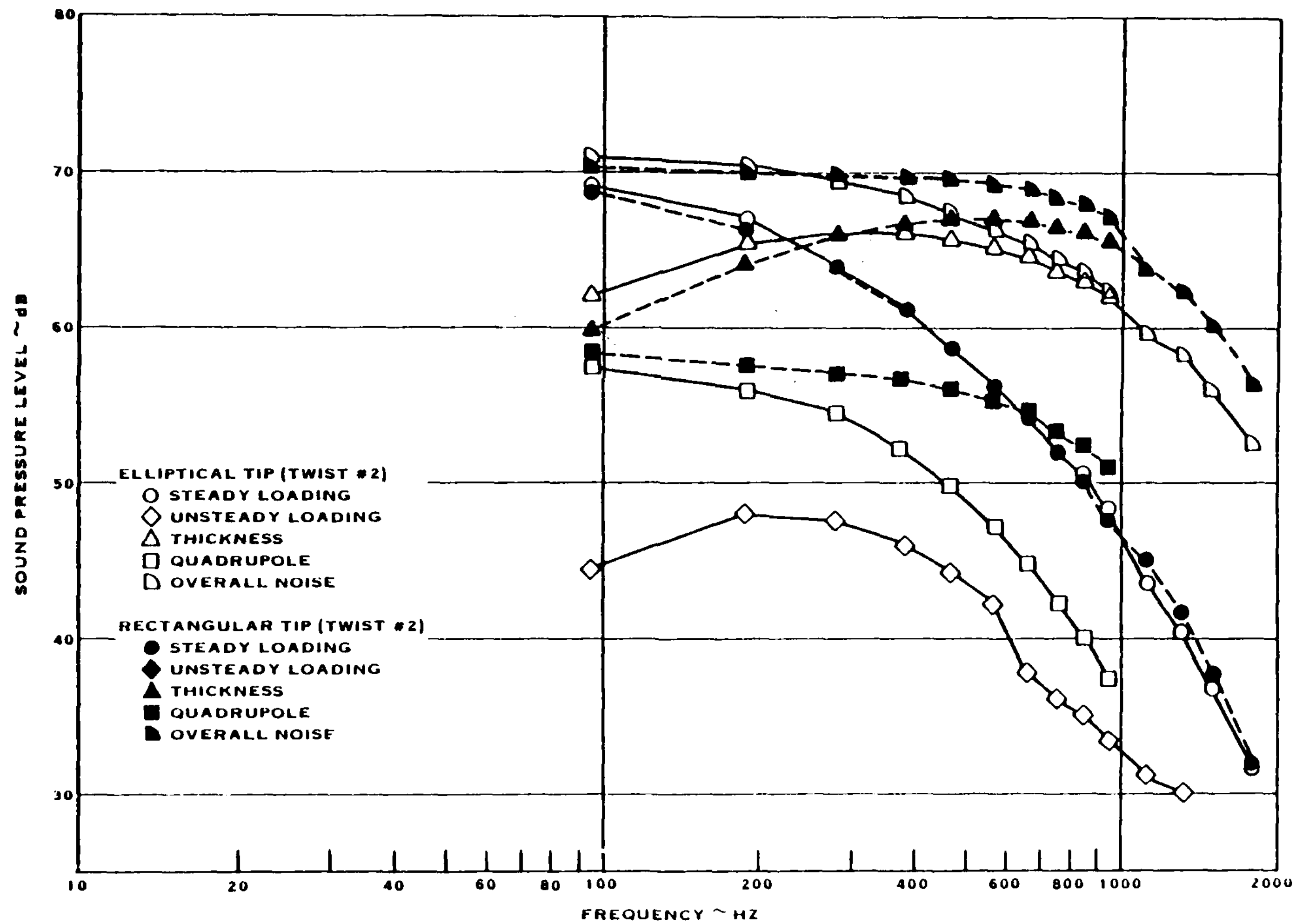


FIGURE 16. EFFECT OF TIP SHAPE ON NOISE COMPONENTS

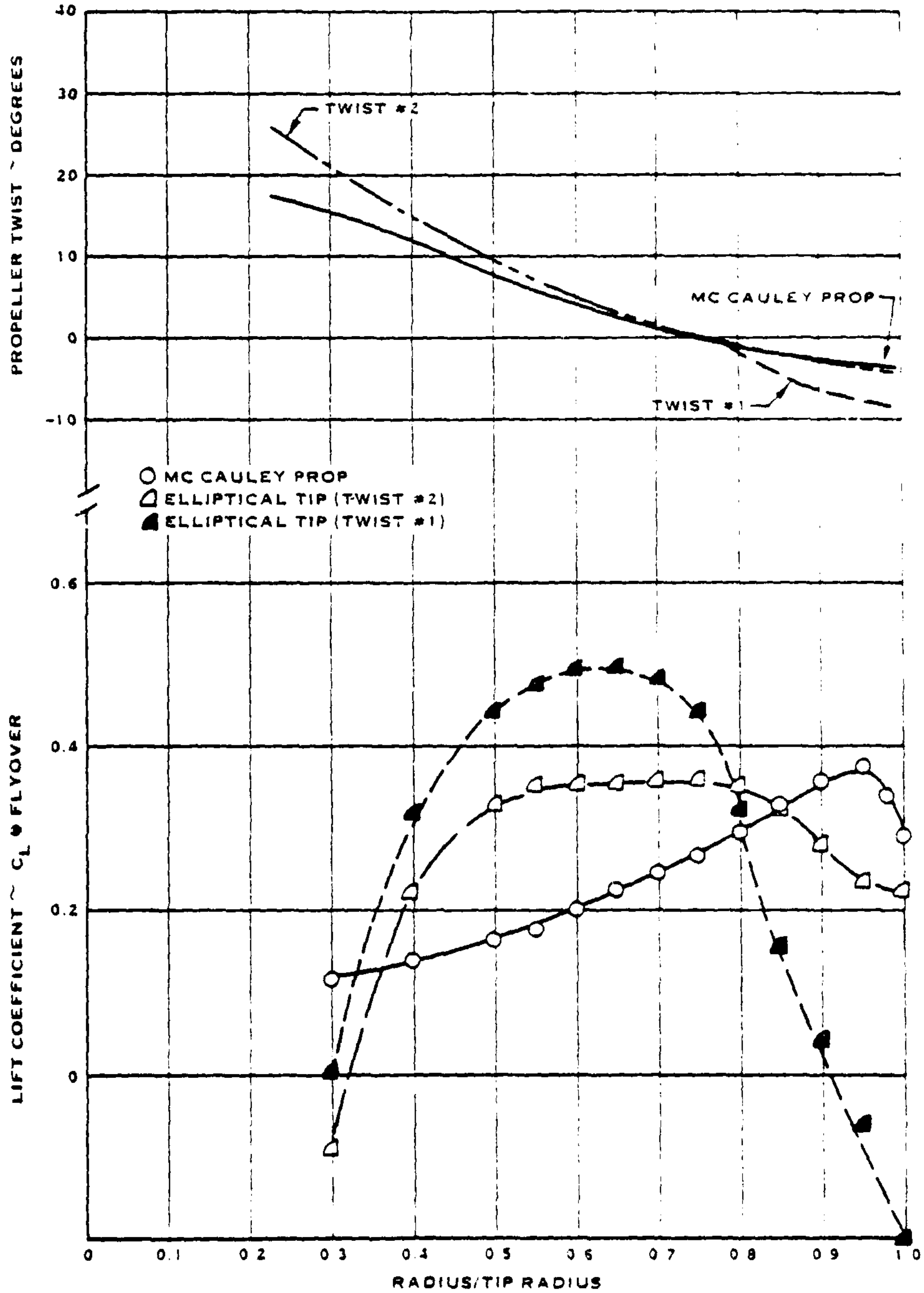


FIGURE 17. COMPARISON OF C_L AND TWIST DISTRIBUTIONS FOR SINGLE ENGINE AIRCRAFT

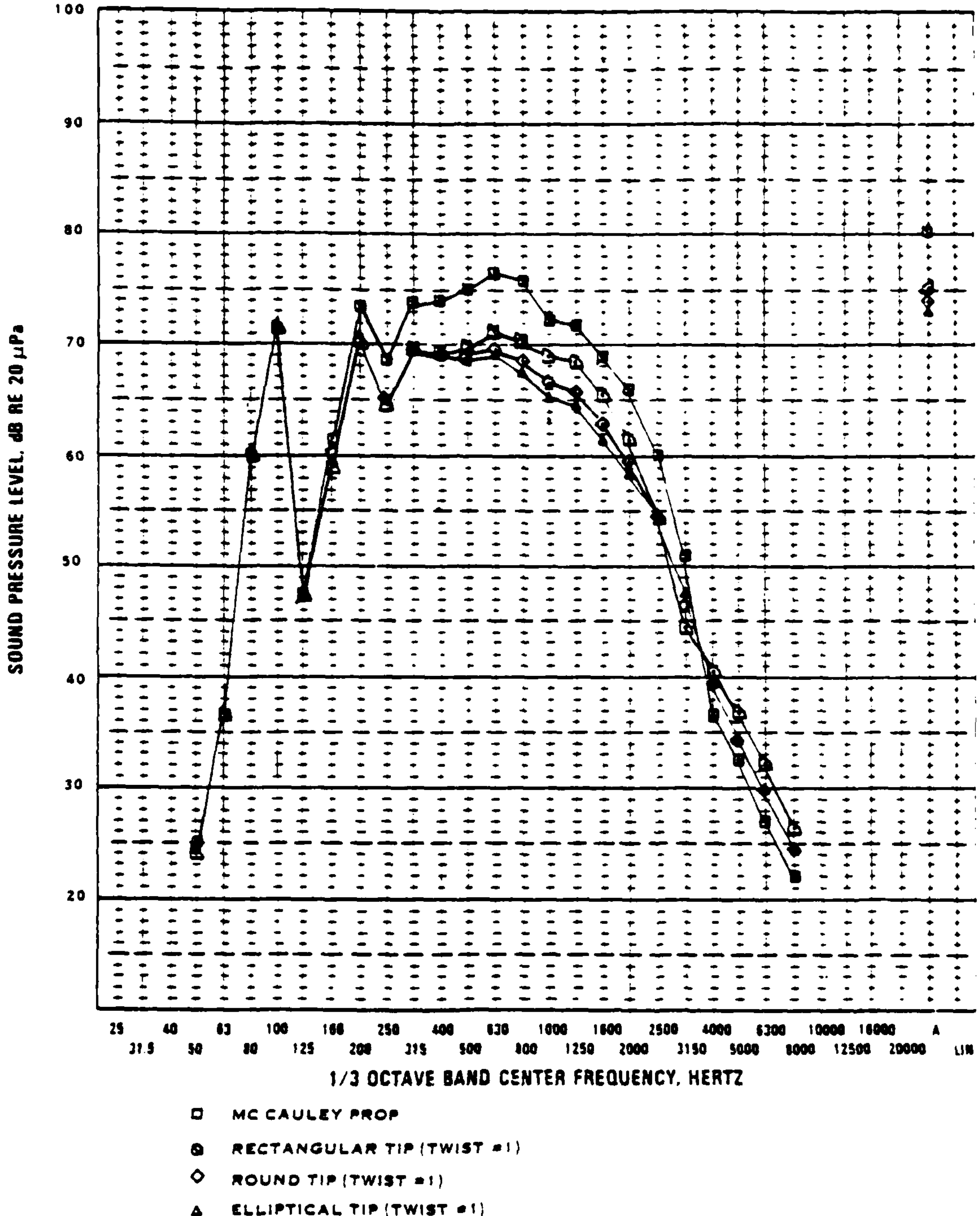


FIGURE 18. EFFECT OF TIP SHAPE ON ONE THIRD OCTAVE BAND SPECTRA FOR LIGHTLY LOADED TIP CONFIGURATIONS

ONE THIRD OCTAVE BAND ANALYSIS

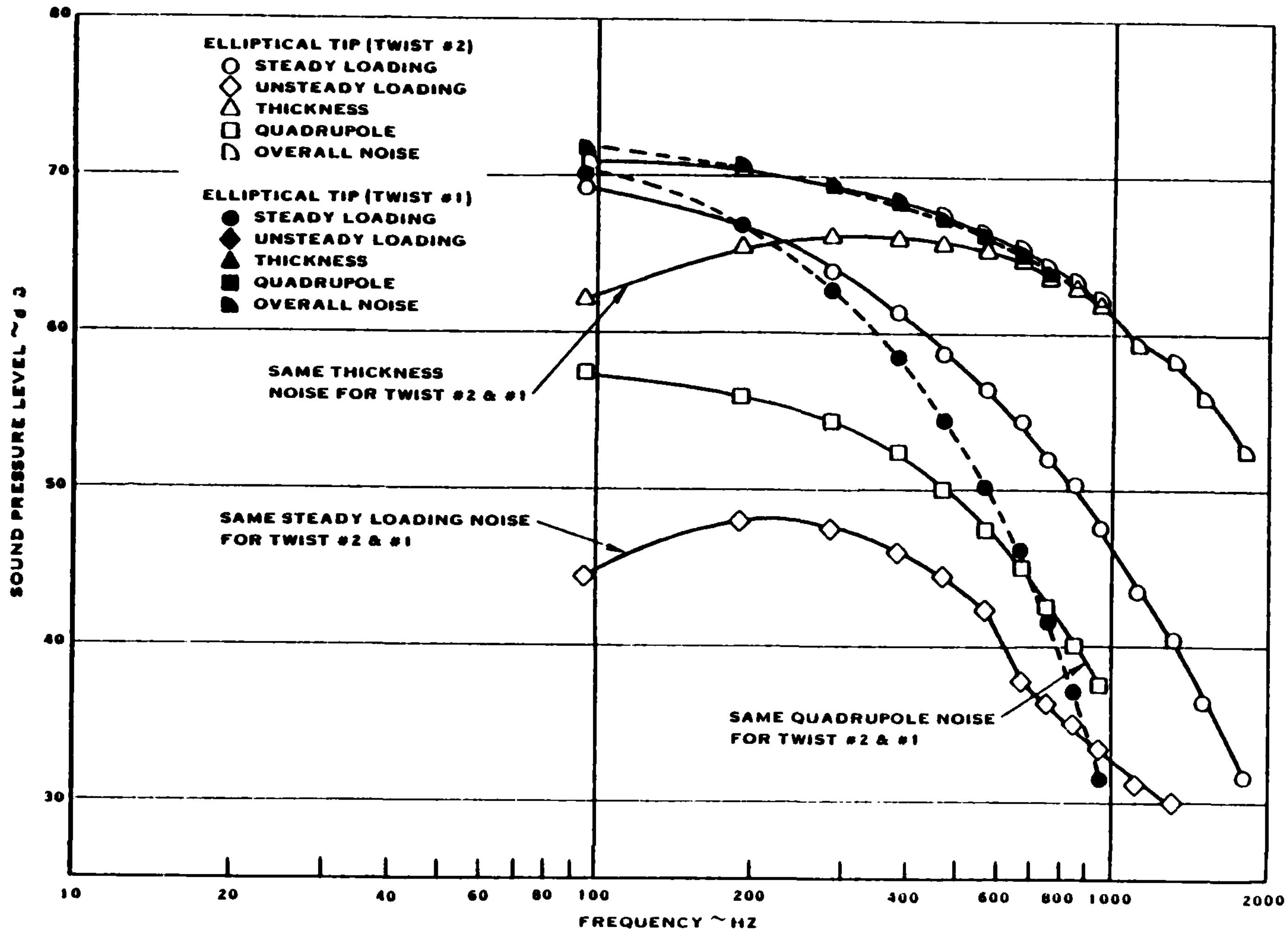
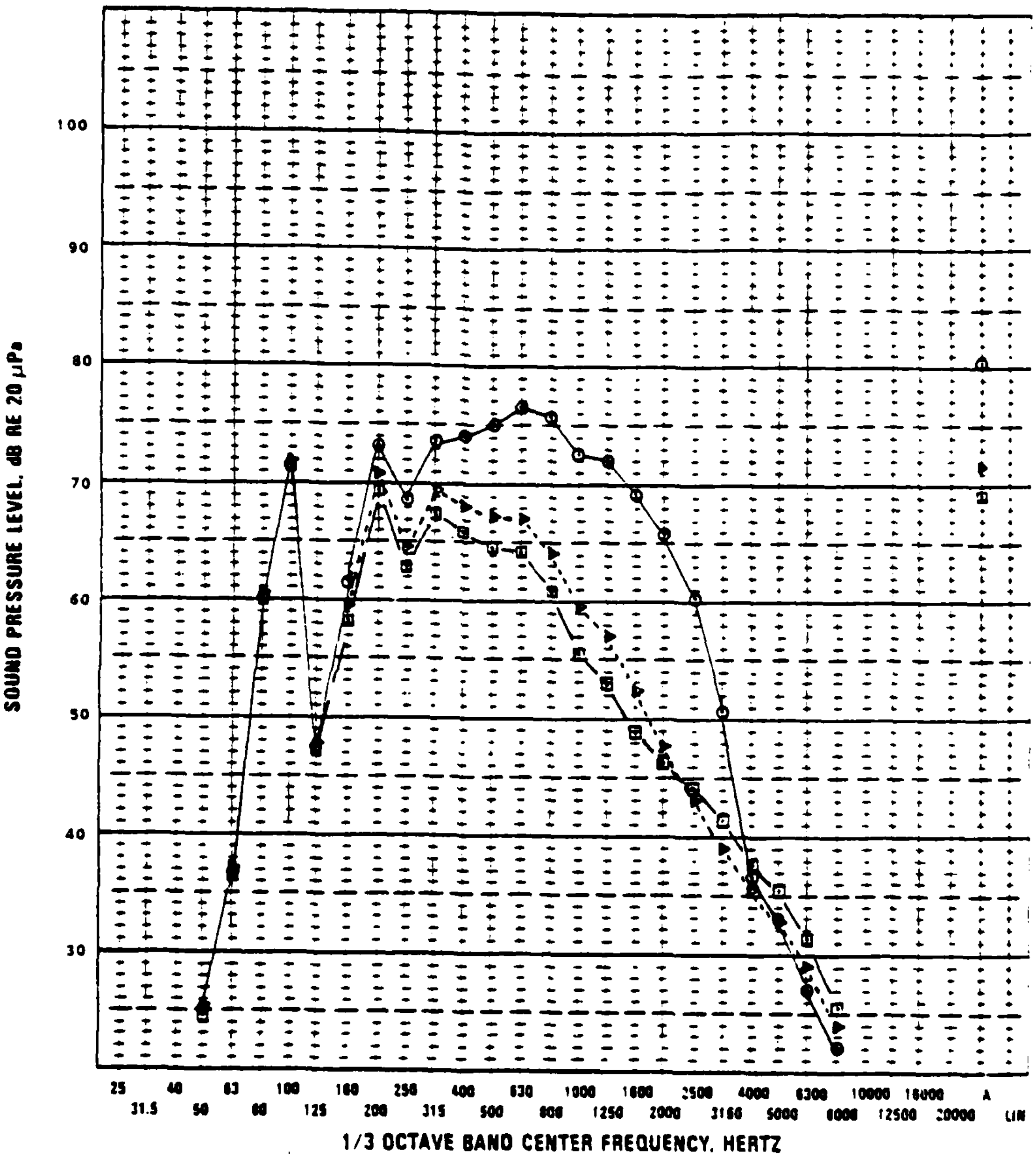


FIGURE 19. EFFECT OF TIP LOADING ON NOISE COMPONENTS



○ CALCULATED MC CAULEY PROP

□ CALCULATED OPTIMUM CONFIGURATION
THIN ELLIPTICAL TIP, 2 BLADES, 6.5 FT

▷ CALCULATED ALTERNATE OPTIMUM CONFIGURATION
THICK ELLIPTICAL TIP, 2 BLADES, 6.5 FT

ONE THIRD
OCTAVE BAND
ANALYSIS

FIGURE 20. DEBONAIR FLYOVER NOISE SPECTRA

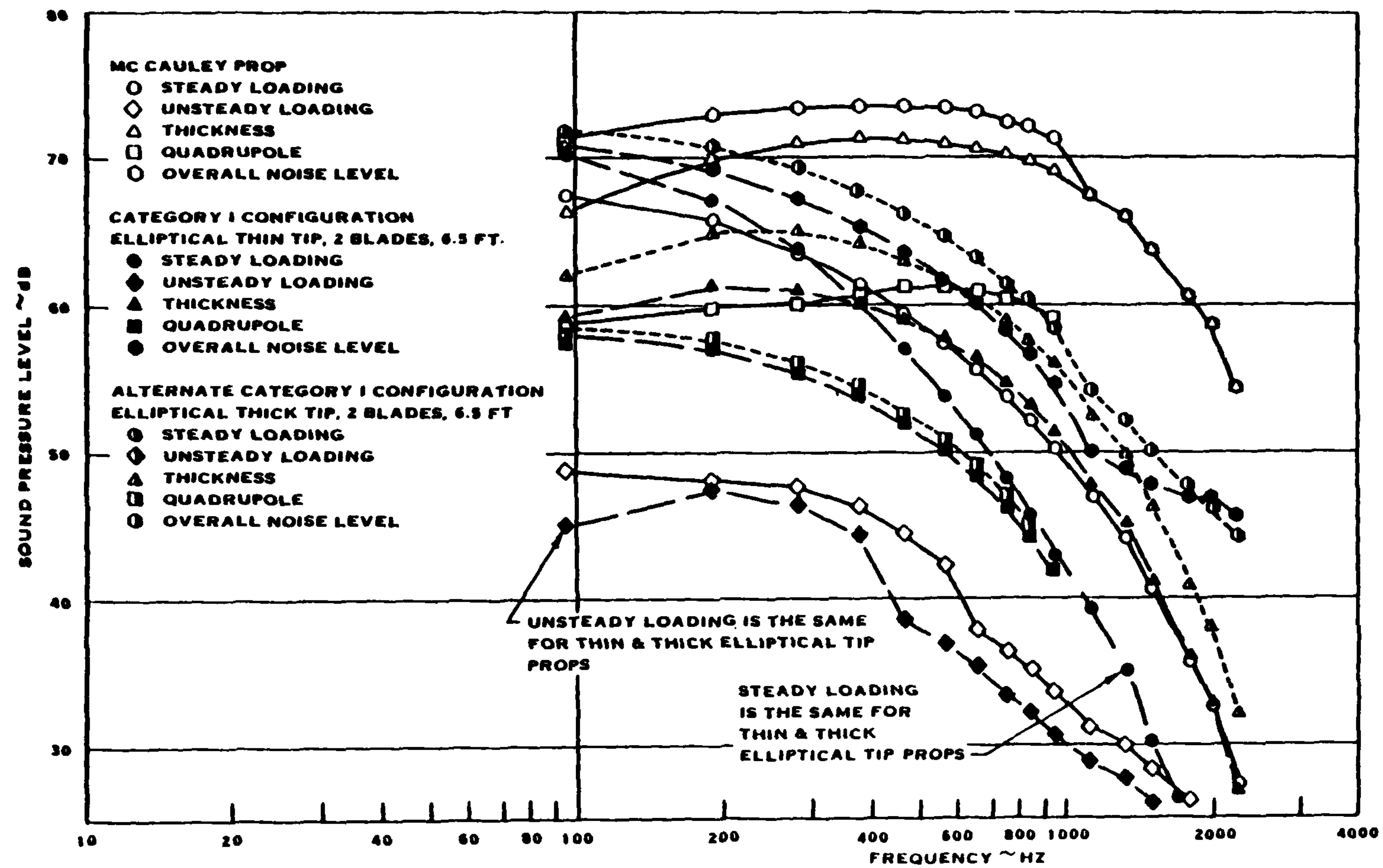


FIGURE 21. DEBONAIR NOISE COMPONENTS

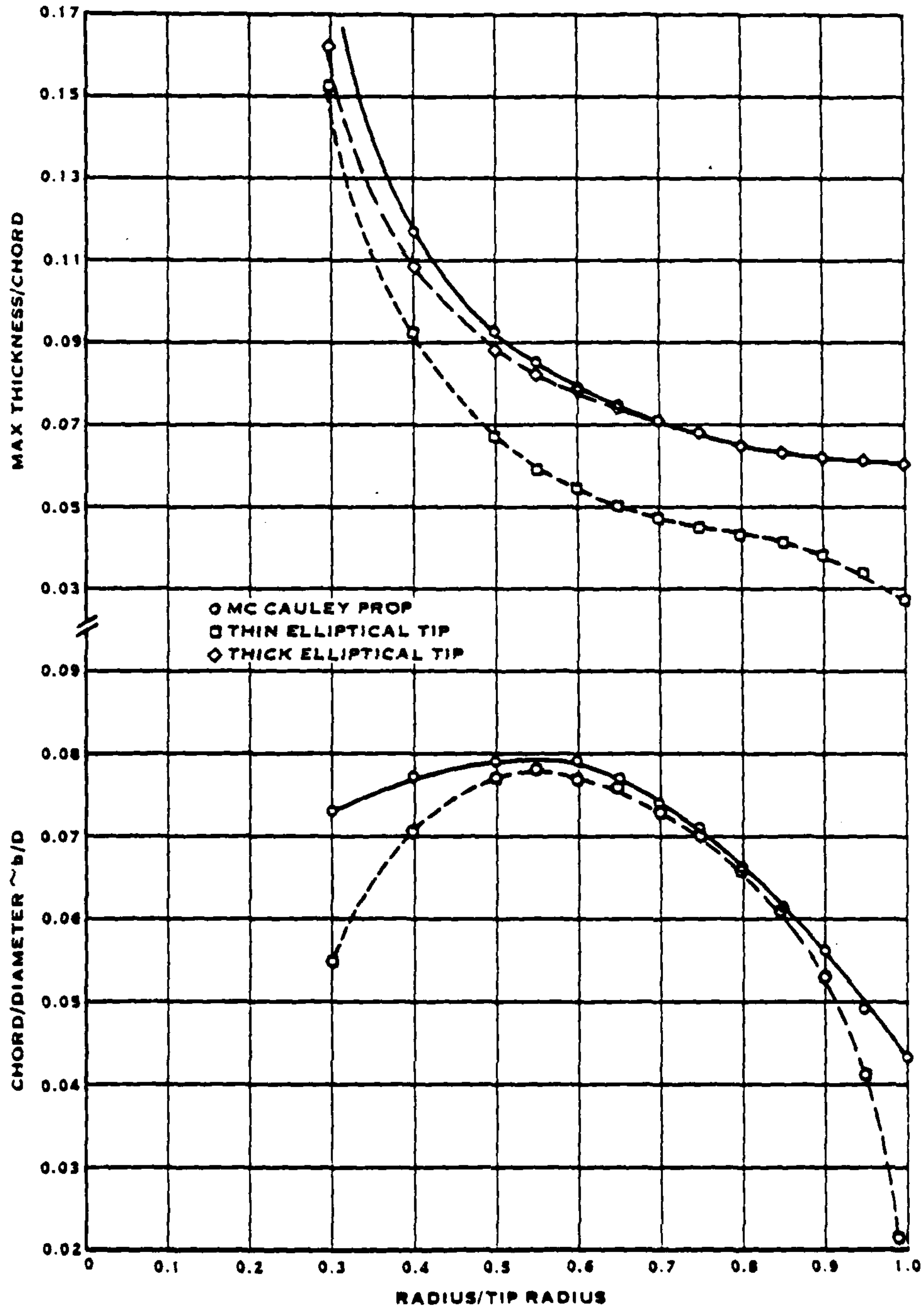


FIGURE 22. DEBONAIR GEOMETRY COMPARISON

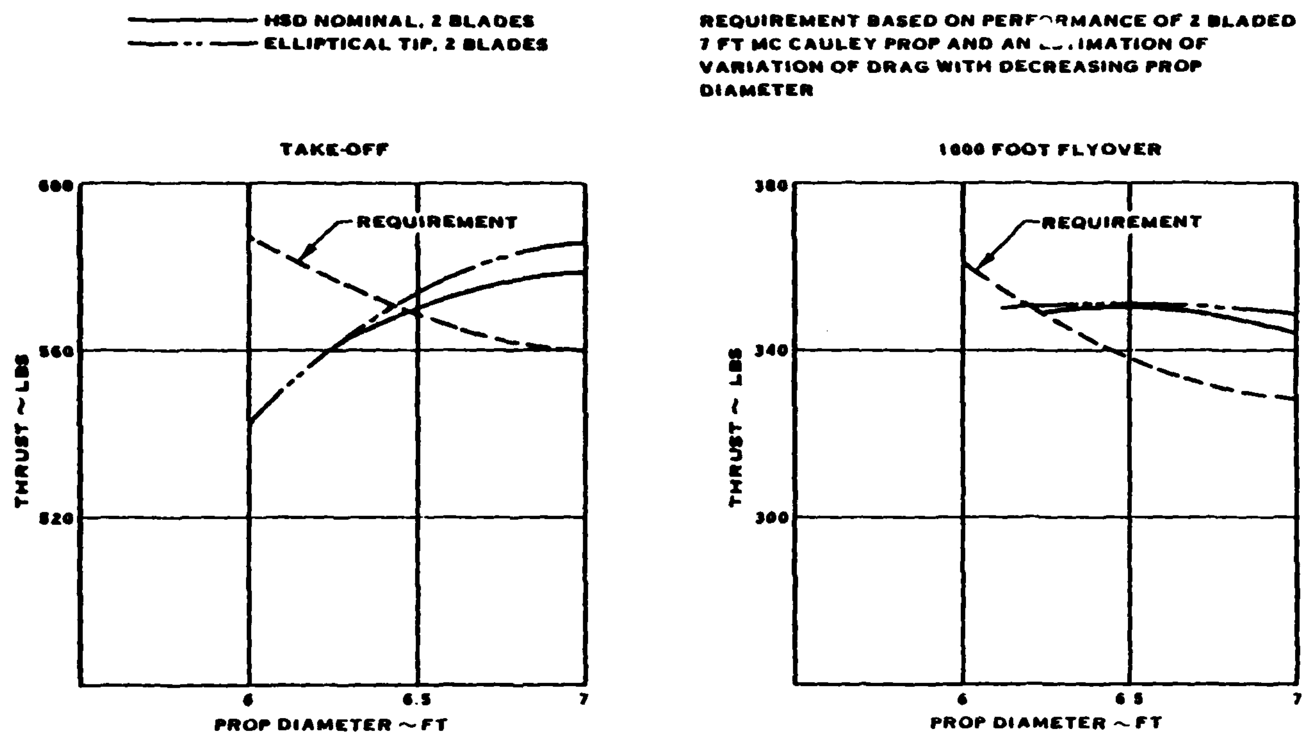


FIGURE 23. PERFORMANCE OF 2 BLADE PROPELLER CONFIGURATIONS FOR BEECH 35-B33 DEBONAIR

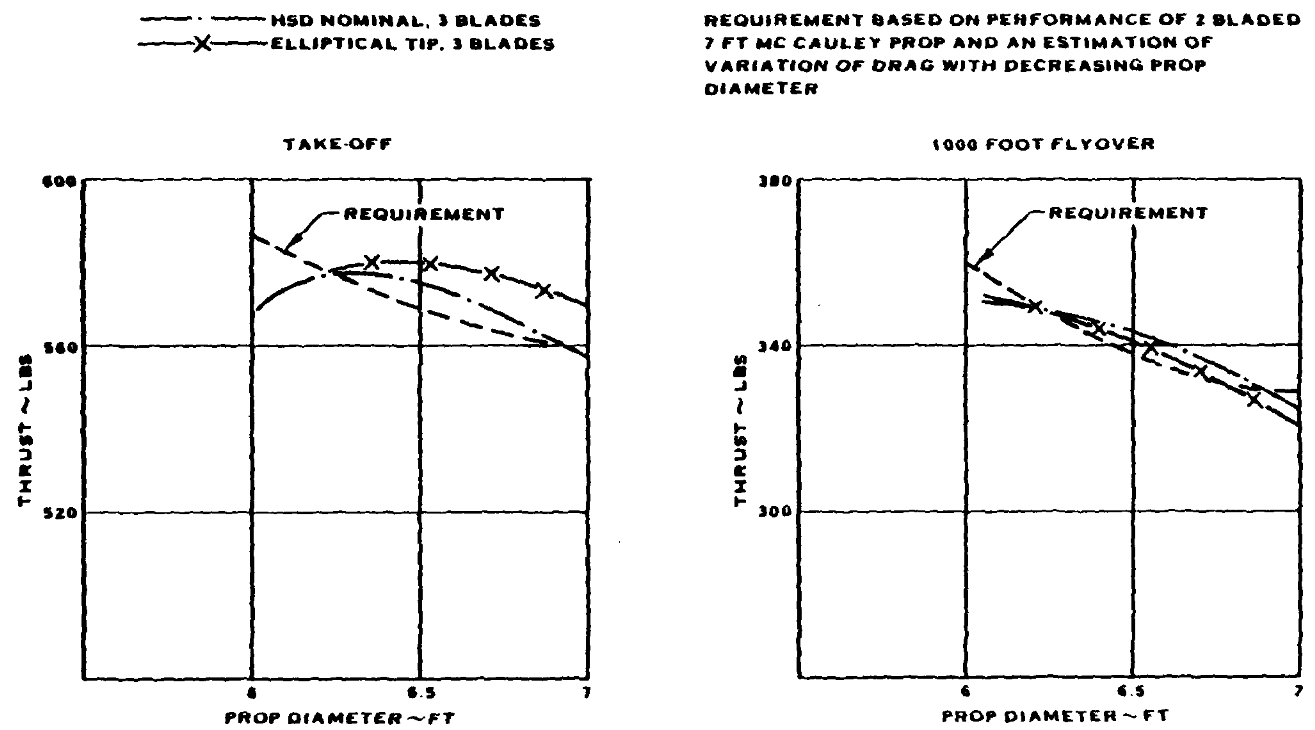


FIGURE 24. PERFORMANCE OF 3 BLADE PROPELLER CONFIGURATIONS FOR BEECH 35-B33 DEBONAIR

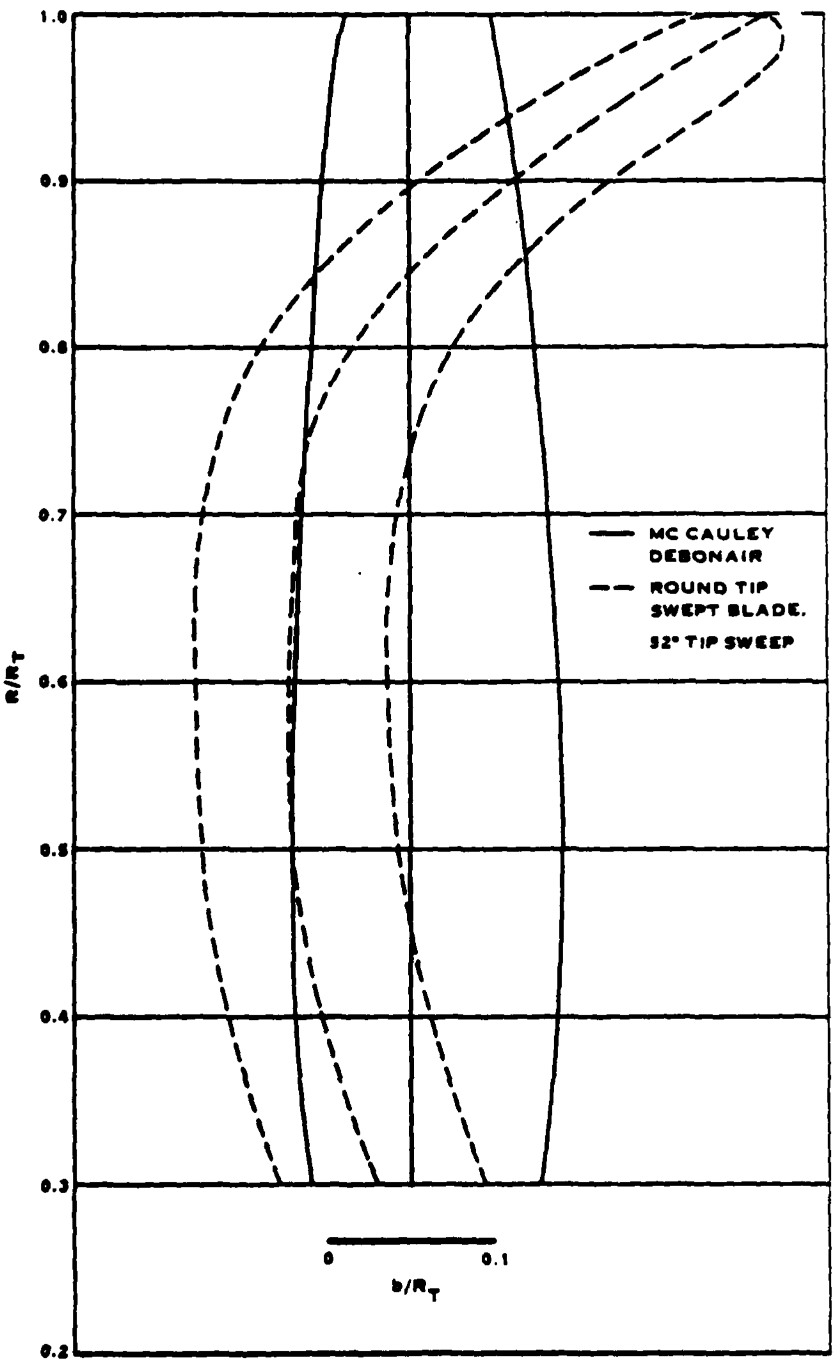
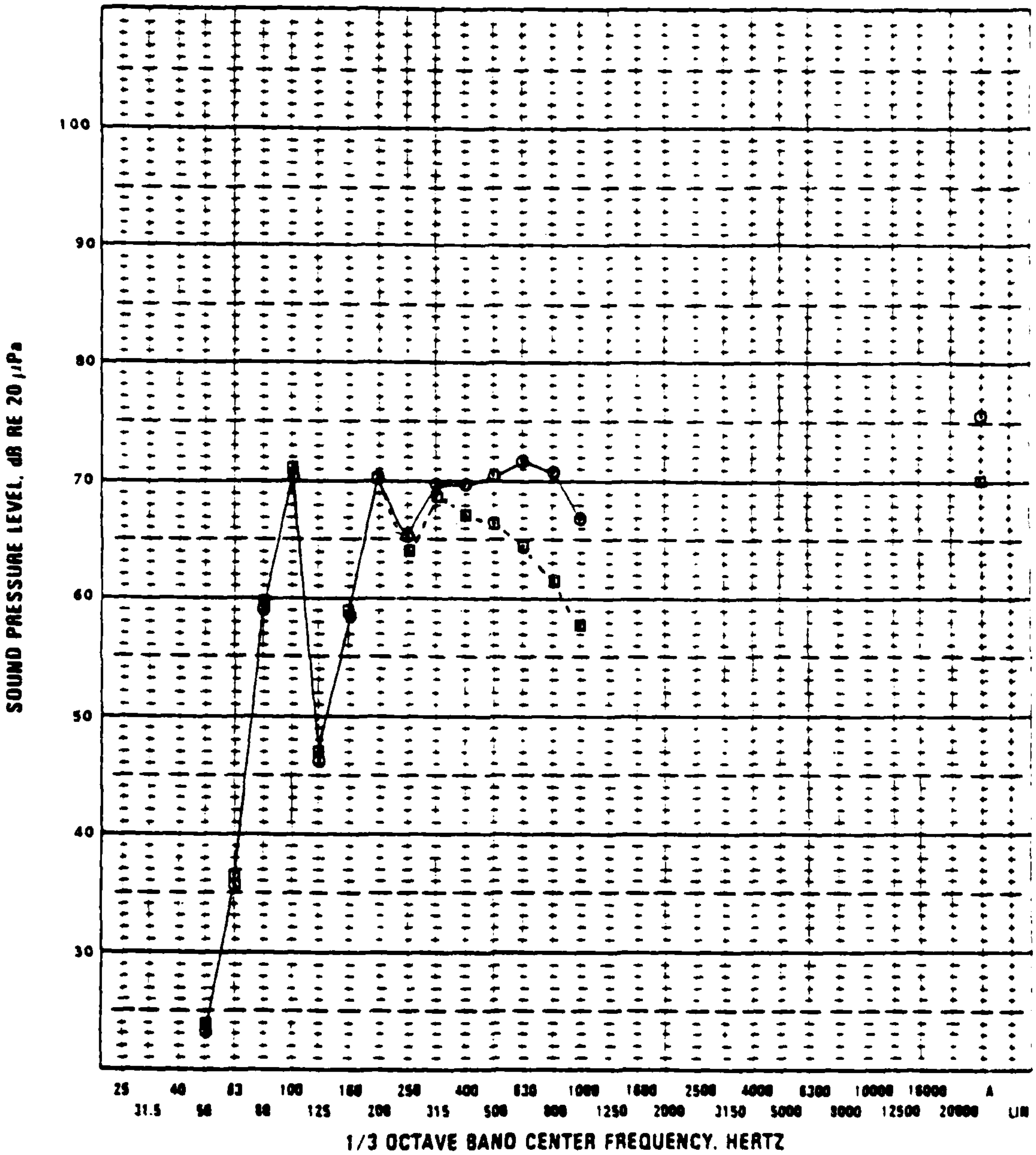


FIGURE 25. SINGLE ENGINE DEBONAIR PROPELLER PLANFORMS



○ 2 BLADES, 7 FT, NOMINAL LOADING, ROUND TIP PROP
□ 2 BLADES, 7 FT, NOMINAL LOADING, ROUND TIP PROP WITH 32° TIP SWEEP

ONE THIRD OCTAVE BAND ANALYSIS

FIGURE 26. DEBONAIR SWEPT BLADE NOISE SPECTRA

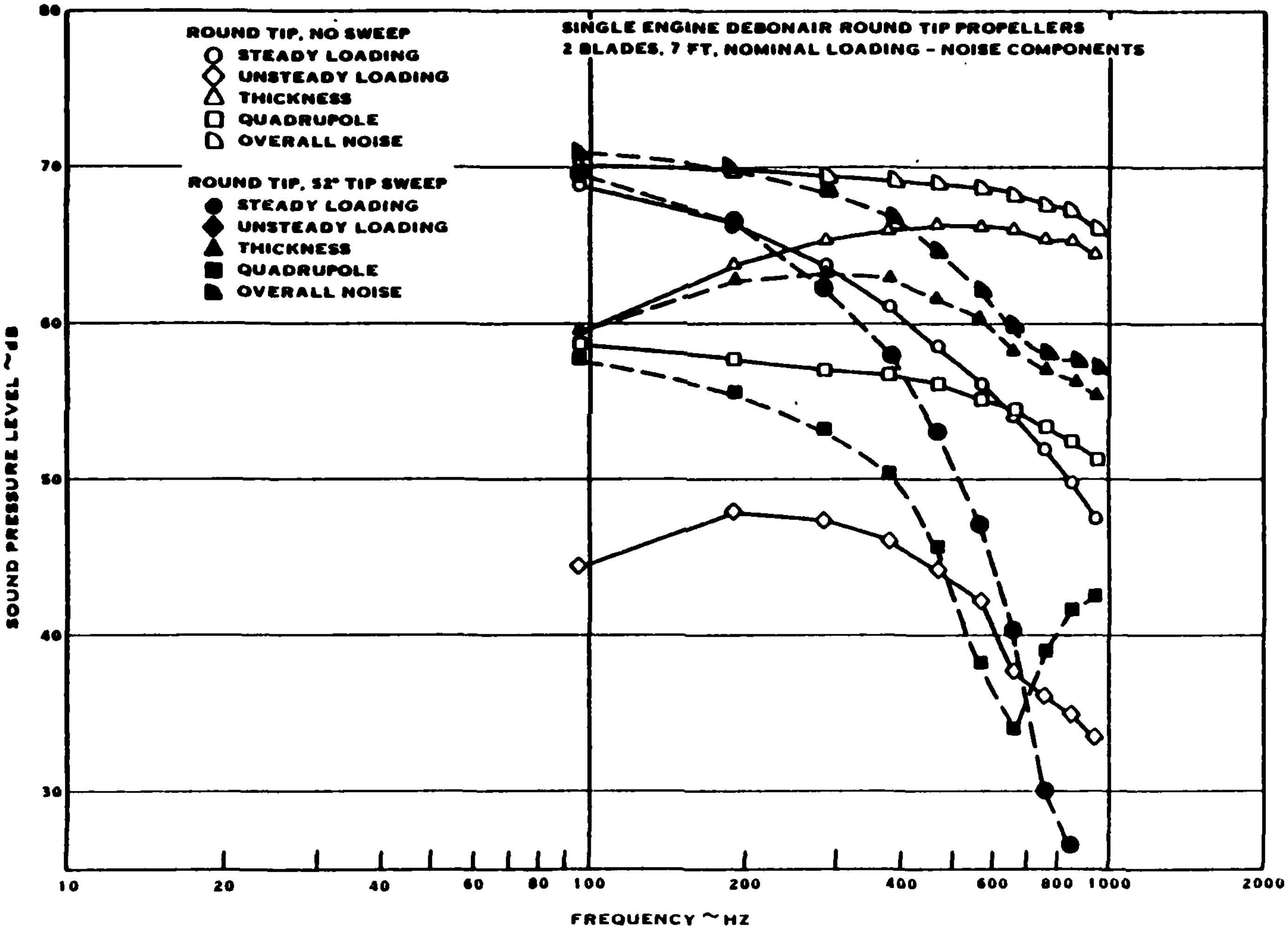


FIGURE 27. DEBONAIR SWEEP VS. NO SWEEP

CONFIGURATION	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
DIAMETER (FT)	7	7	7	7	7	7	7	7	7	7	6.5	6.5	7	6.25	6.5	6.25	6.25	6.25	6.25
NO. BLADES	2	2	2	2	2	2	2	2	2	2	2	2	2	3	2	3	3	3	3
AIRFOIL	RAF-6	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16
TIP LOADING	N	N	N	N	N	N	R	R	N	R	N	N	N	N	N	N	N	N	N
TIP SHAPE	N	RO	E	N	RE	RO	RE	RO	E	E	E	N	RO	E	E	N	E	RO	RO
TIP THICKNESS	TK	TK	TK	TH	TH	TH	TH	TH	TH	TH	TK	TH	TH	TK	TH	TH	TH	TK	TH
TIP SWEEP	0°	0°	0°	0°	0°	0°	0°	0°	0°	0°	0°	0°	52°	0°	0°	0°	0°	52°	52°

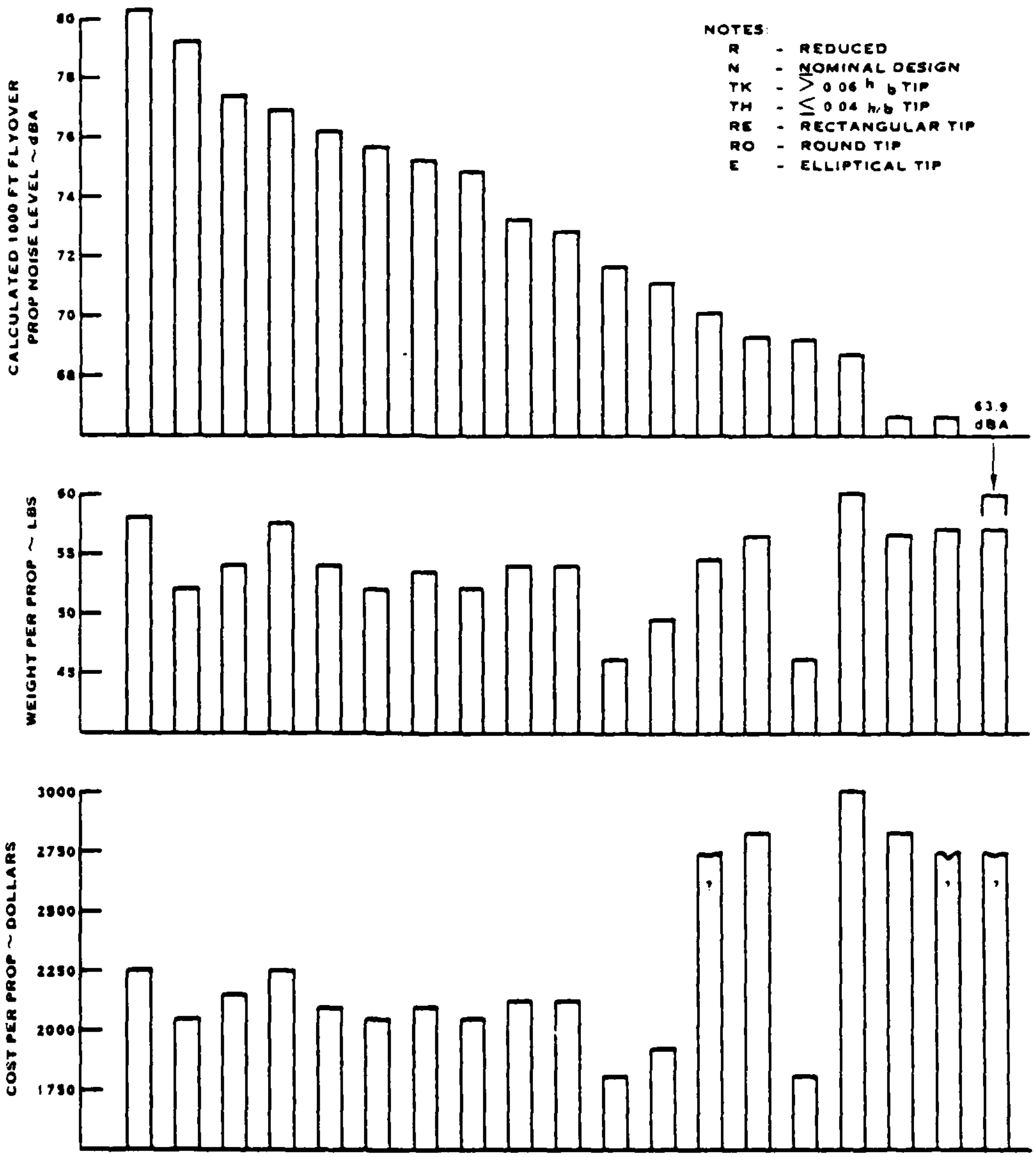


FIGURE 28. BEECH DEBONAIR SUMMARY

CONFIGURATION	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
DIAMETER (FT)	7	7	7	7	7	7	7	7	7	7	6.5	6.5	7	6.25	6.5	6.25	6.25	6.25	6.25
NO. BLADES	2	2	2	2	2	2	2	2	2	2	2	2	2	3	2	3	3	3	3
AIRFOIL	RAF-6	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16
TIP LOADING	N	N	N	N	N	N	R	R	N	R	N	N	N	N	N	N	N	N	N
TIP SHAPE	N	RO	E	N	RE	RO	RE	RO	E	E	E	N	RO	E	E	N	E	RO	RO
TIP THICKNESS	TK	TK	TK	TH	TH	TH	TH	TH	TH	TH	TK	TH	TH	TK	TH	TH	TH	TK	TH
TIP SWEEP	0°	0°	0°	0°	0°	0°	0°	0°	0°	0°	0°	0°	52°	0°	0°	0°	0°	52°	52°

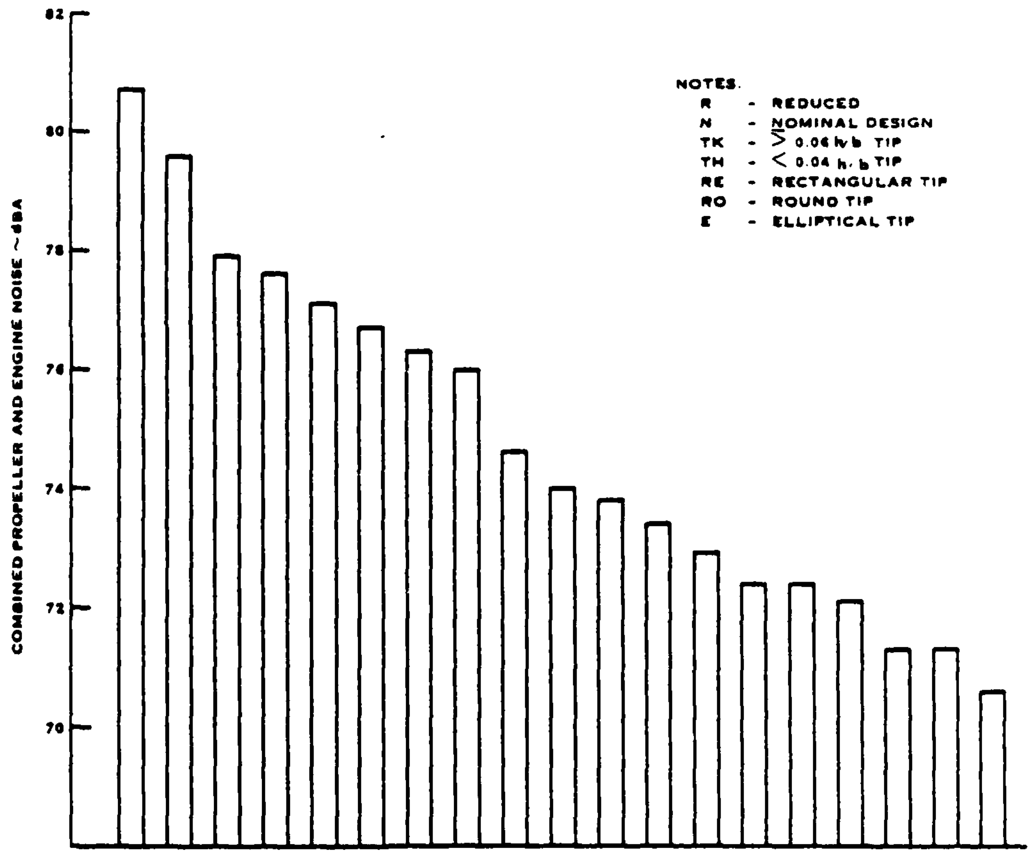


FIGURE 29. ESTIMATED COMBINED PROPELLER AND ENGINE NOISE FOR SINGLE ENGINE DEBONAIR

DISCUSSION

Study of Light Twin Engine Aircraft

The Beech 76 Duchess was selected as the reference aircraft for the light twin engine aircraft category. The Duchess was selected because noise data was available for the verification of the noise prediction methodology. Also, the relatively low level of flyover noise indicated that the Duchess propeller should represent General Aviation aircraft with better than average noise control.

For the single engine aircraft study, the promising low noise approaches were found to include tip chord reduction (elliptical tip), tip thickness reduction, optimized performance (to reduce diameter) and addition of more blades to obtain the maximum diameter reduction. These approaches to reducing propeller noise were applied to reducing propeller noise levels for Duchess replacement propellers. Based on the above design approaches, a total of 10 replacement configurations were evaluated for the Duchess. Figure 30 summarizes the noise levels, weight, and cost for these 10 propellers. Detailed descriptions of the propeller configurations of Figure 30 are presented in Table III. The impact of propeller noise reductions upon overall aircraft flyover noise was evaluated by estimation of a combined engine and propeller noise level by the same method as used for the Debonair study discussed earlier. Combined engine and propeller noise levels for the configuration of Figure 30 are shown in Figure 31.

Configurations 2, 3, and 5 are two-blade propellers. Configuration 5 shows the largest noise reduction for the two-blade replacement propellers, 3.8 dBA, with a 12% weight reduction and a 13% cost reduction. From Figure 30, it can be seen that configuration 5 provides the largest noise reduction with no weight or cost penalty and is, therefore, the category 2 replacement configuration. The 3.8 dBA reduction in propeller noise level was the result of reducing airfoil tip thickness and propeller diameter. As shown in Figure 32, the base Duchess blade had a planform shape that was already very close to the elliptical tip favored for reduced noise so that little tip chord reduction could be accomplished. However, the Duchess propeller had a relatively thick tip (h/b) as shown in Figure 33 so that a reduction in tip thickness could be incorporated in the elliptical tip designs which are also defined in Figure 33.

As mentioned in the Debonair study, the replacement propellers all utilize Series 16 airfoils. As in the case of the Debonair study, the Duchess propeller did not use NACA Series 16 airfoils. Instead, Clark Y airfoils were used in the Duchess design. Analysis of the Duchess and replacement propellers showed better performance for the replacement propellers at the same diameter due to better airfoil performance and more thorough performance optimization. As shown in Figure 34, the better performance of the two-blade replacement propellers allowed use of a smaller diameter. As in the Debonair study, the increased thrust required when a smaller diameter propeller is used was calculated as described in Appendix E. As seen from Figure 34, a 0.4 ft. diameter reduction was acceptable. This is configuration 5 in Figure 30. A 3.8 dBA noise reduction for configuration 5 was found which is due to the reduction in tip thickness and the 0.4 foot diameter reduction which reduces tip speed at equal RPM. Configuration 5 provided an estimated 2.7 dBA reduction in combined engine and propeller noise as shown in Figure 31. Figure 35 shows that further diameter reductions are feasible for a 3 blade propeller.

Configurations 4 and 6 through 9 are three-blade propeller designs based on the findings in Figure 35. Configuration 8 shows the largest noise reduction of the 3 blade replacement propellers (6.5 dBA). Configuration 4 is a thick tip 3 blade propeller and has a noise level 3.2 dBA higher than configuration 8, a thin elliptical tip design. This is attributed to the difference in thickness. Configuration 7, a three-blade nominal planform propeller shows a 5.2 dBA noise reduction, however, the tip chord for this blade (as seen in Figure 32 and 33) is slightly wider than the Duchess and the elliptical tip replacement propellers. As shown in Figure 33, the blade is thicker than the elliptical tip propeller. As in the Debonair study, the elliptical tip planform was found to be the best low noise design. Configurations 8 and 9 show the effects of reduced tip C_L for a 3 blade Duchess replacement propeller. As previously concluded, reduced tip C_L does not appear to be an effective low noise design approach for lightly loaded General Aviation aircraft propellers. The reduction in loading noise is offset by the noise caused by the increase in propeller diameter which is required to maintain the performance of the low tip C_L propeller. Therefore, as Figure 33 shows, configuration 9 offers no noise reduction relative to configuration 8 which is the nominal tip laoding. Configuration 8 shows a 0.58 foot diameter reduction, the largest obtainable with a 3-blade replacement propeller. The 6.5 dBA propeller noise reduction for configuration 8 was attributed to the reduction in tip thickness and the 0.58 foot diameter reduction. The 3-blade replacement propellers all have cost penalties and all except configuration 7 have weight penalties. Configuration 8 has a 2% weight penalty and a 20% cost penalty and is the most cost effective of the 3-blade replacement propellers as seen from Figure 30. Estimated reduction in combined engine and propeller noise was 3.8 dBA from Figure 31.

Figure 36 shows that 4 blade reduced diameter replacement propellers will meet the aircraft thrust requirement. Configurations 10 and 11 of Figure 30 are 4 blade propellers. Configuration 11 showed the greatest noise reduction (an 8.6 dBA reduction) of all the configurations evaluated. While no swept blade replacement propellers were evaluated for the light twin engine study, it is expected that they would show further reductions from that achieved by configuration 11. The 8.6 dBA noise reduction obtained with configuration 11 was due to the reduction in tip thickness and the diameter reduction. As indicated in Figure 30, a 0.68 foot diameter reduction relative to the existing Duchess propeller was used for configuration 11. Again, the elliptical tip blade was the best propeller noise reduction configuration.

The first and second noise reduction goals were achieved with configuration 5, a thin elliptical tip 2 blade propeller with reduced diameter. A 3.8 dBA reduction in propeller noise was found for this configuration with a 13% weight reduction and a 12% cost reduction. Figure 31 shows that the aircraft noise reduction for this configuration is 2.7 dBA.

The third noise reduction goal was achieved with configuration 11, a thin elliptical tip 4 blade propeller with reduced diameter. An 8.6 dBA reduction in propeller noise was found for this configuration with a 13% weight penalty and a 59% cost penalty. Figure 31 shows that the aircraft noise reduction for this configuration is 4.4 dBA. The small reduction in aircraft noise for this configuration is due to the large engine noise contribution. If noise reductions like those achieved with configuration 11 are of interest, then engine muffling should be considered.

In summary, it was found in the light twin engine study for the Duchess, that the thickness noise dominated the existing propeller. However, the Duchess planform is already very similar to the elliptical tip shape found most promising for low noise in the Debonair study. Some noise reduction was obtained by reducing the thickness to chord ratio of the replacement blades relative to the existing Duchess blade. A reduction in combined engine and propeller noise level of 2.7 dBA was estimated for a 2 blade configuration with reductions in weight of 12% per propeller and a reduction cost of 13% per propeller. Further noise reductions required weight and/or cost penalties. The low noise propeller configuration which provided the maximum noise reduction for the least weight and cost penalties was a 3 blade, 5.75 foot, thin elliptical tip propeller. This low noise propeller provided a 6.5 dBA reduction in propeller noise level for a 2% per propeller weight penalty and a 22% per propeller cost penalty. However, this reduction in propeller noise was estimated to give only a 3.3 dBA reduction in combined engine and propeller noise level based on an unmuffled engine exhaust. To utilize the full potential of the above propeller, the engine noise level should be reduced. It appears that significant cost and weight penalties involving redesign of both the propeller and the engine exhaust system are required to reduce the flyover noise levels of the Duchess by 5 dBA.

TABLE III

CONFIGU-RATION	NO. OF BLADES	PROPELLER DIAMETER	AIRFOIL SERIES	ACTIVITY FACTOR	b/D @ .75 r	b/D @ .99 r	h/b @ .75 r	h/B TIP	C_{L_O} @ R/KT	C_{L_O} @ TIP	SWEEP ANGLE @ TIP DEGREES	TIP HELI-CAL MN	DESIGN C_{L_1}	TIP SHAPE
1	2	6.33	CLARK-Y	95.3	.074	.028	.078	.067	.166	.258	0^o	.84	.679	--
2	2	6.20	16	80.0	.056	.040	.072	.029	.505	.206	0^o	.81	.508	NOMINAL
3	2	6.10	16	95.7	.067	.047	.066	.027	.446	.163	0^o	.80	.508	NOMINAL
4	3	5.85	16	89.8	.070	.022	.073	.064	.396	.280	0^o	.77	.508	ELLIPTICAL
5	2	6.10	16	89.8	.070	.022	.045	.027	.495	.352	0^o	.80	.508	ELLIPTICAL
6	3	5.85	16	95.7	.067	.047	.066	.027	.347	.116	0^o	.77	.508	NOMINAL
7	3	5.85	16	80.0	.056	.040	.072	.029	.374	.169	0^o	.77	.508	NOMINAL
8	3	5.75	16	89.8	.070	.022	.045	.027	.422	.310	0^o	.76	.508	ELLIPTICAL
9	3	5.85	16	89.8	.070	.022	.045	.027	.443	.001	0^o	.77	.508	ELLIPTICAL
10	4	5.70	16	80	.056	.040	.072	.029	.349	.130	0^o	.75	.508	NOMINAL
11	4	5.65	16	80	.063	.022	.047	.029	.383	.285	0^o	.74	.508	ELLIPTICAL

CONFIGURATION	1	2	3	4	5	6	7	8	9	10	11
DIAMETER (FT)	6.33	6.2	6.1	5.85	6.10	5.85	5.75	5.75	5.85	5.70	5.65
NO. BLADES	2	2	2	3	2	3	3	3	3	4	4
AIRFOILS	CL	16	16	16	16	16	16	16	16	16	16
TIP LOADING	N	N	N	N	N	N	N	N	R	N	N
TIP SHAPE	N	N	N	E	E	N	N	E	E	N	E
TIP THICKNESS	TK	TH	TH	TK	TH	TH	TH	TH	TH	TH	TH
ACTIVITY FACTOR	95.3	80	95.7	89.8	89.8	95.7	80	89.8	89.8	80	80

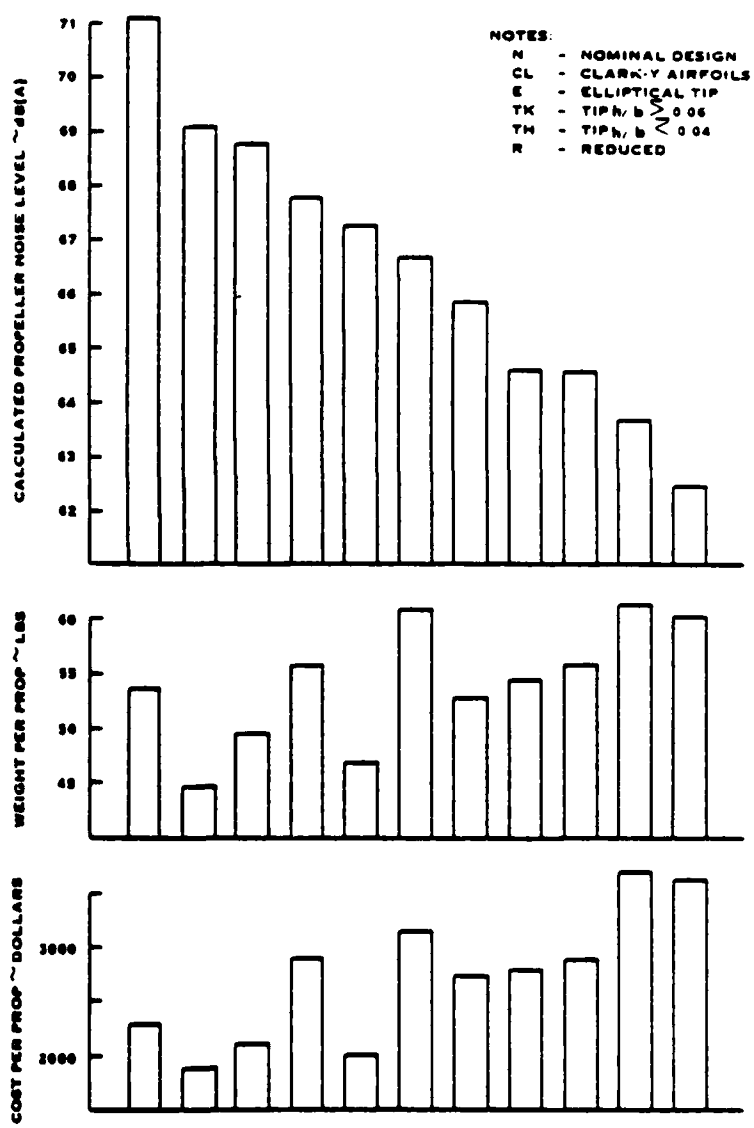


FIGURE 30. BEECH 76 DUCHESS SUMMARY

CONFIGURATION	1	2	3	4	5	6	7	8	9	10	11
DIAMETER (FT)	6.33	6.2	6.1	5.85	6.10	5.85	5.75	5.75	5.85	5.70	5.65
NO. BLADES	2	2	2	3	2	3	3	3	3	4	4
AIRFOILS	CL	16	16	16	16	16	16	16	16	16	16
TIP LOADING	N	N	N	N	N	N	N	N	R	N	N
TIP SHAPE	N	N	N	E	E	N	N	E	E	N	E
TIP THICKNESS	TK	TH	TH	TK	TH	TH	TH	TH	TH	TH	TH
ACTIVITY FACTOR	95.3	80	95.7	89.8	89.8	95.7	80	89.8	89.8	80	80

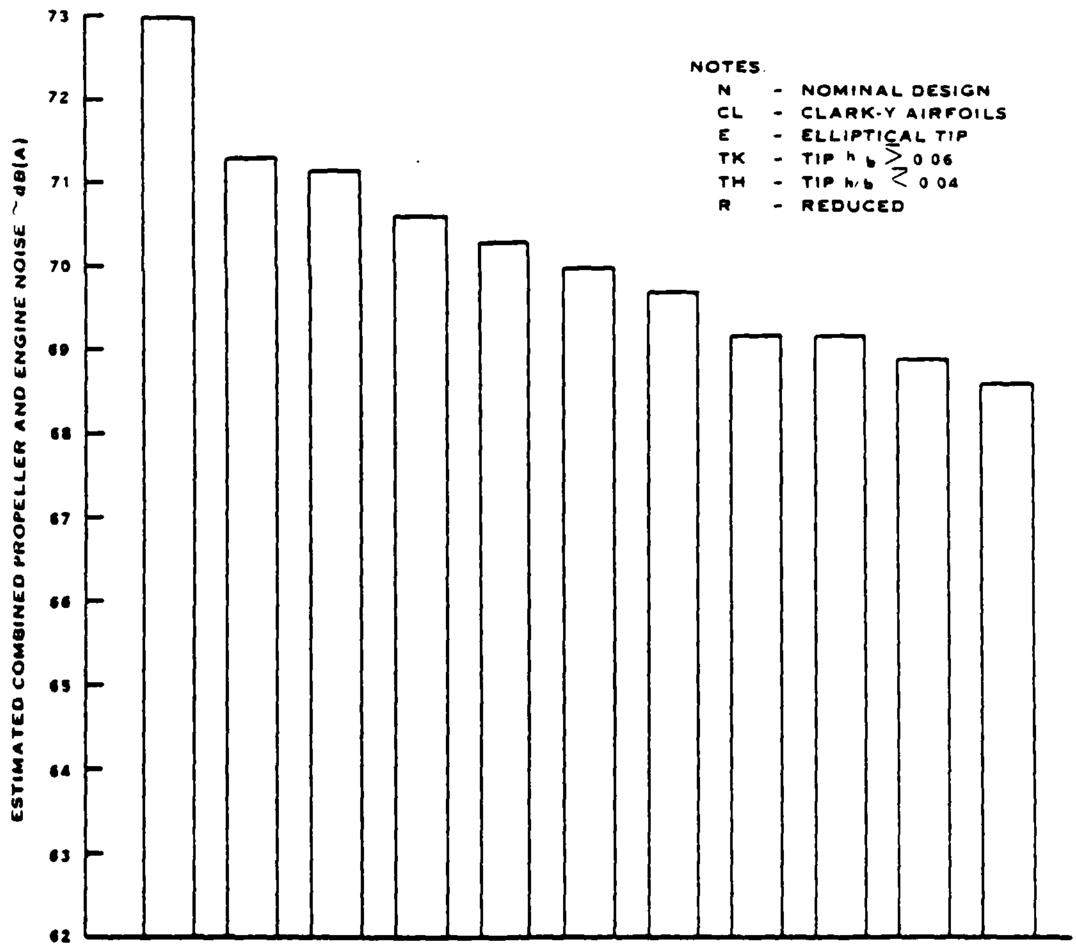


FIGURE 31. ESTIMATED COMBINED PROPELLER AND ENGINE NOISE FOR BEECH 76 DUCHESS

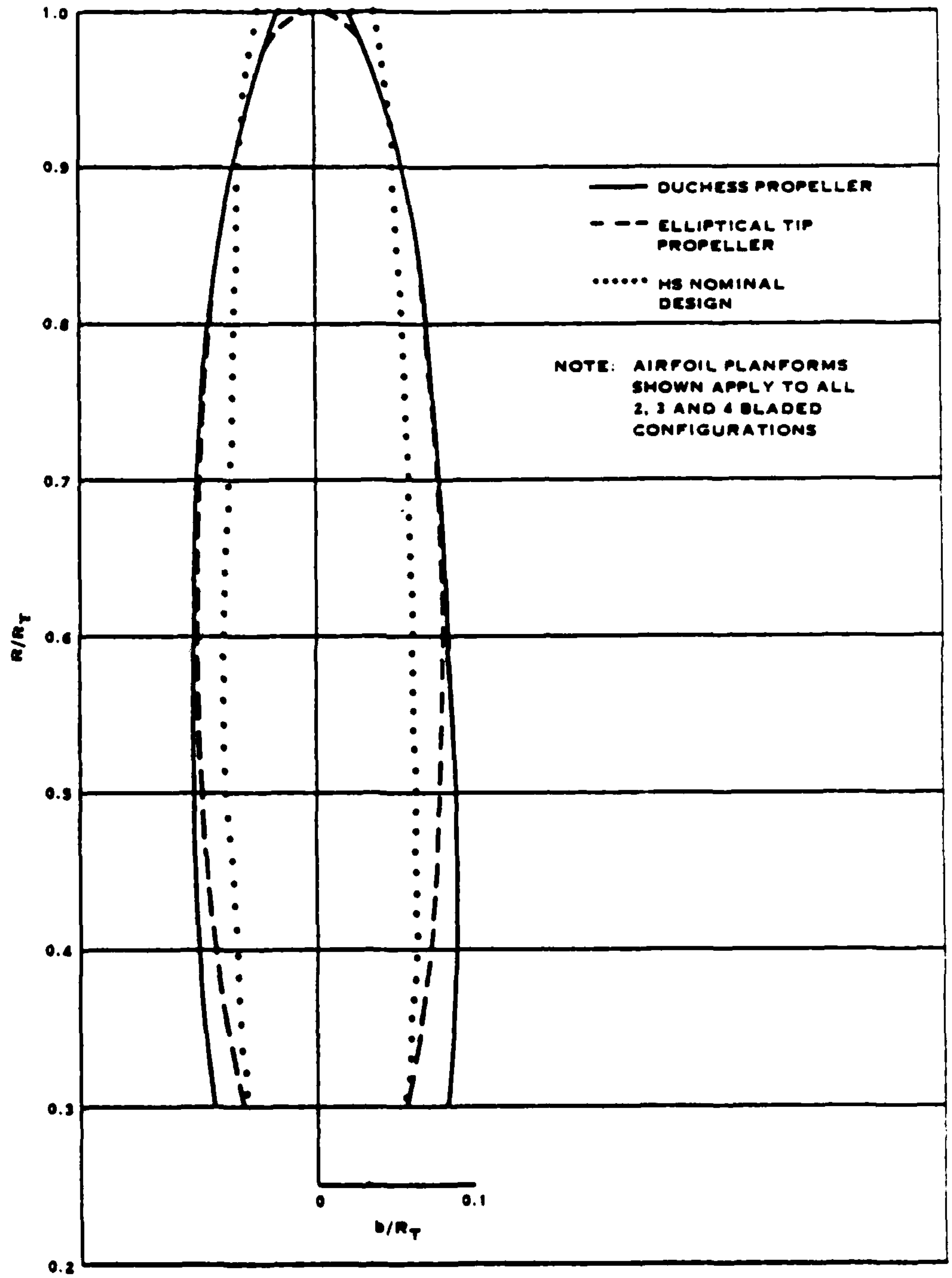


FIGURE 32. BEECH 76 DUCHESS PROPELLER PLANFORMS

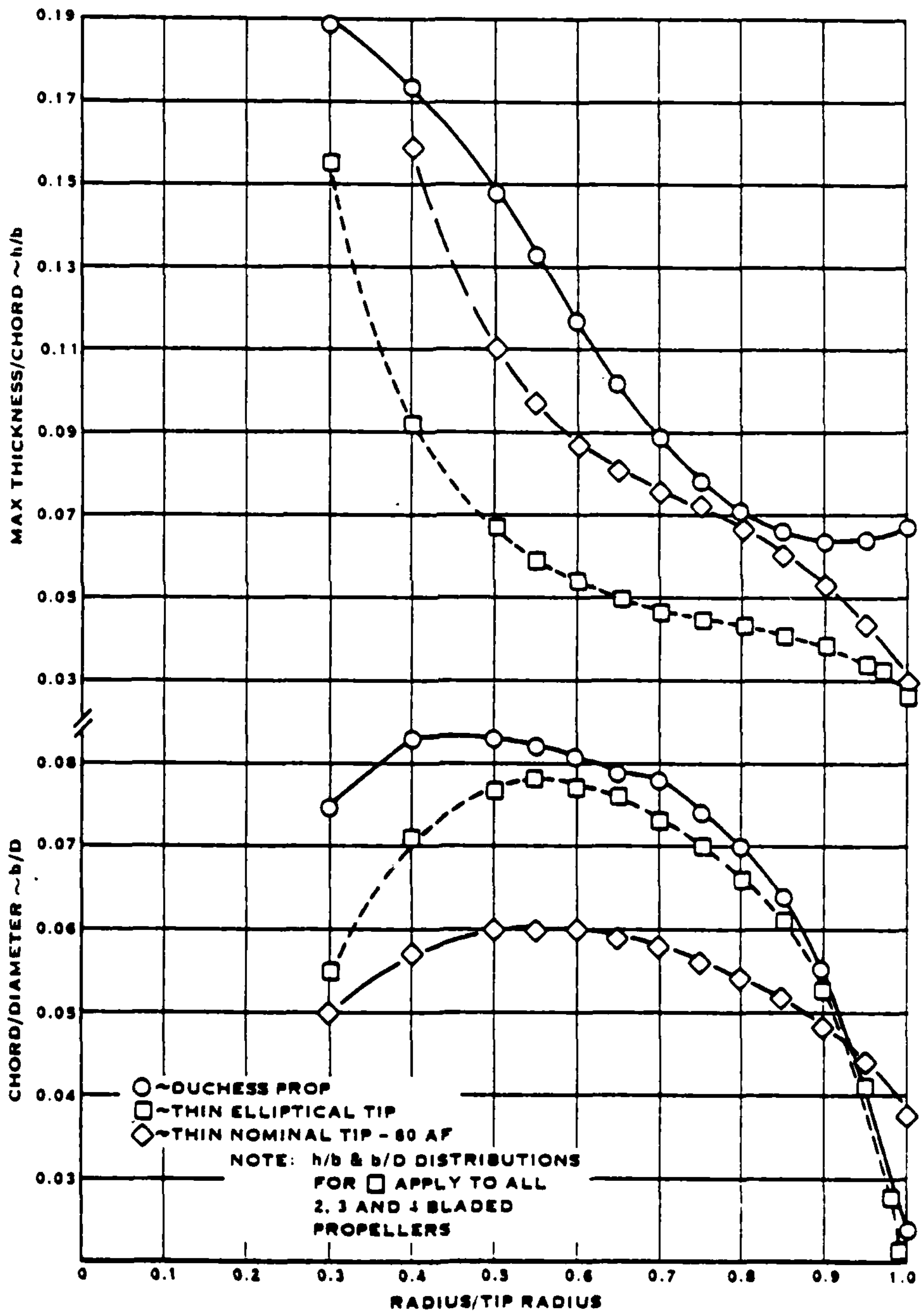


FIGURE 33. BEECH 76 DUCHESS GEOMETRY COMPARISON

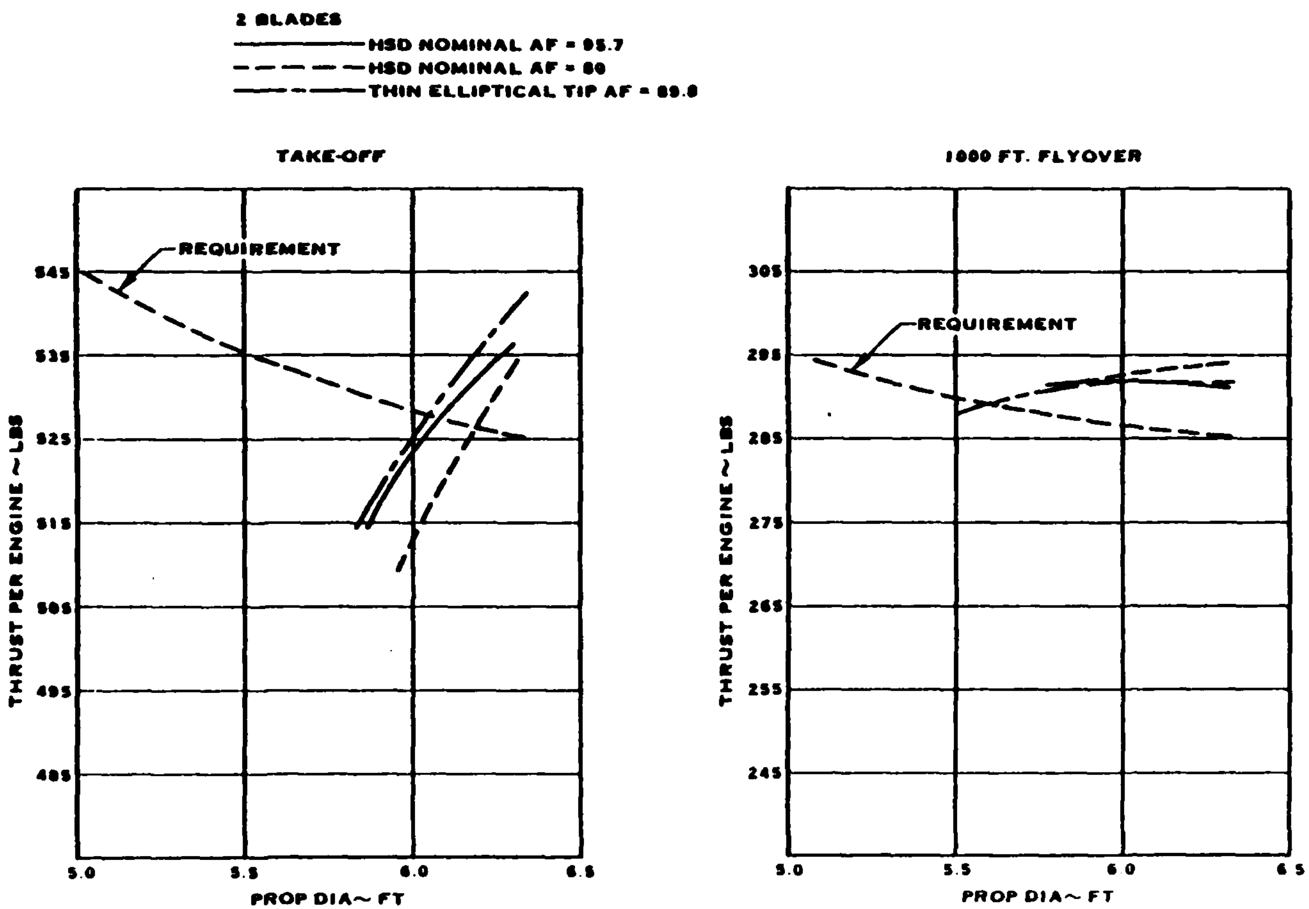


FIGURE 34. BEECH 76 DUCHESS PERFORMANCE REQUIREMENTS VS. DIAMETER

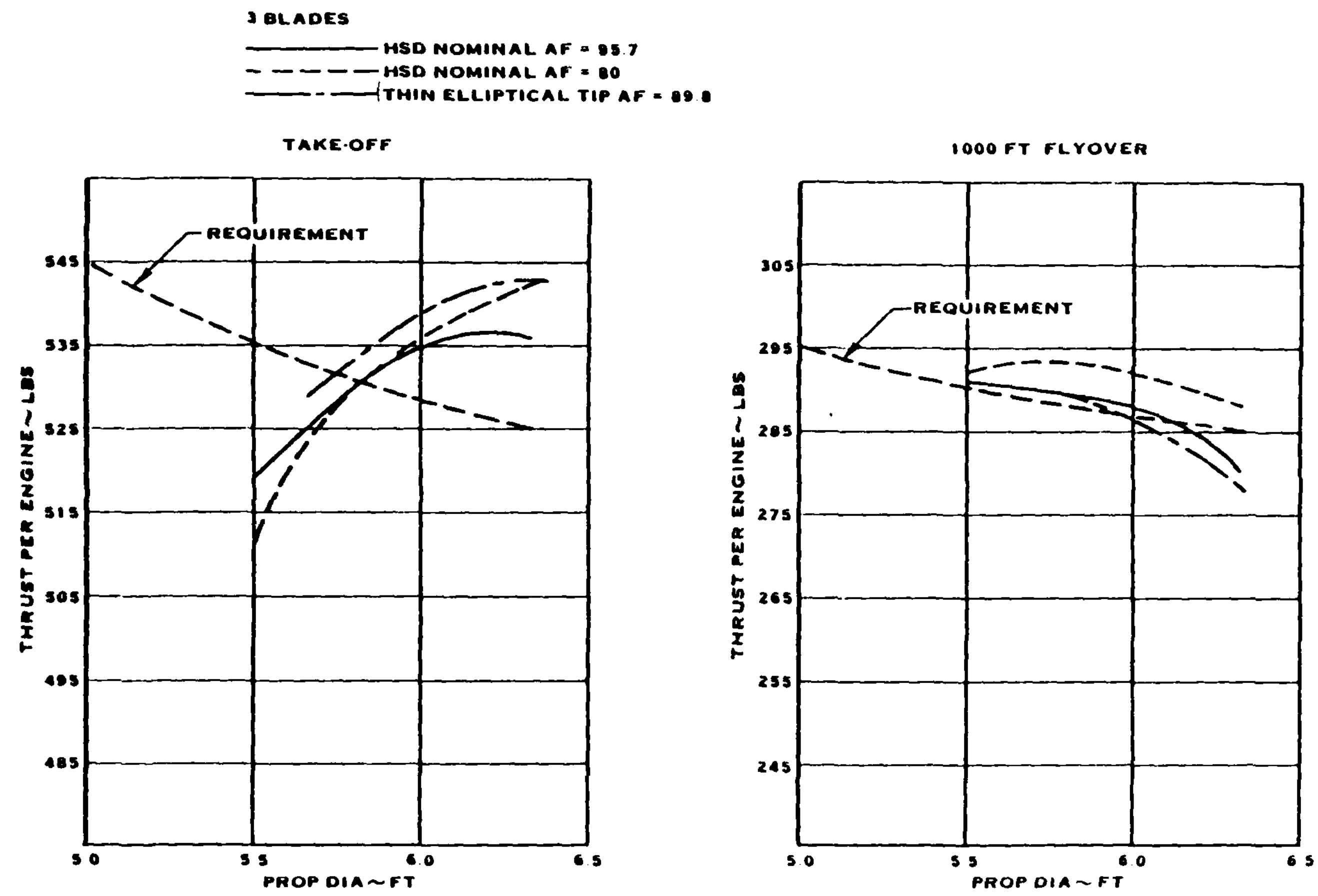


FIGURE 35. BEECH 76 DUCHESS PERFORMANCE REQUIREMENTS VS. DIAMETER

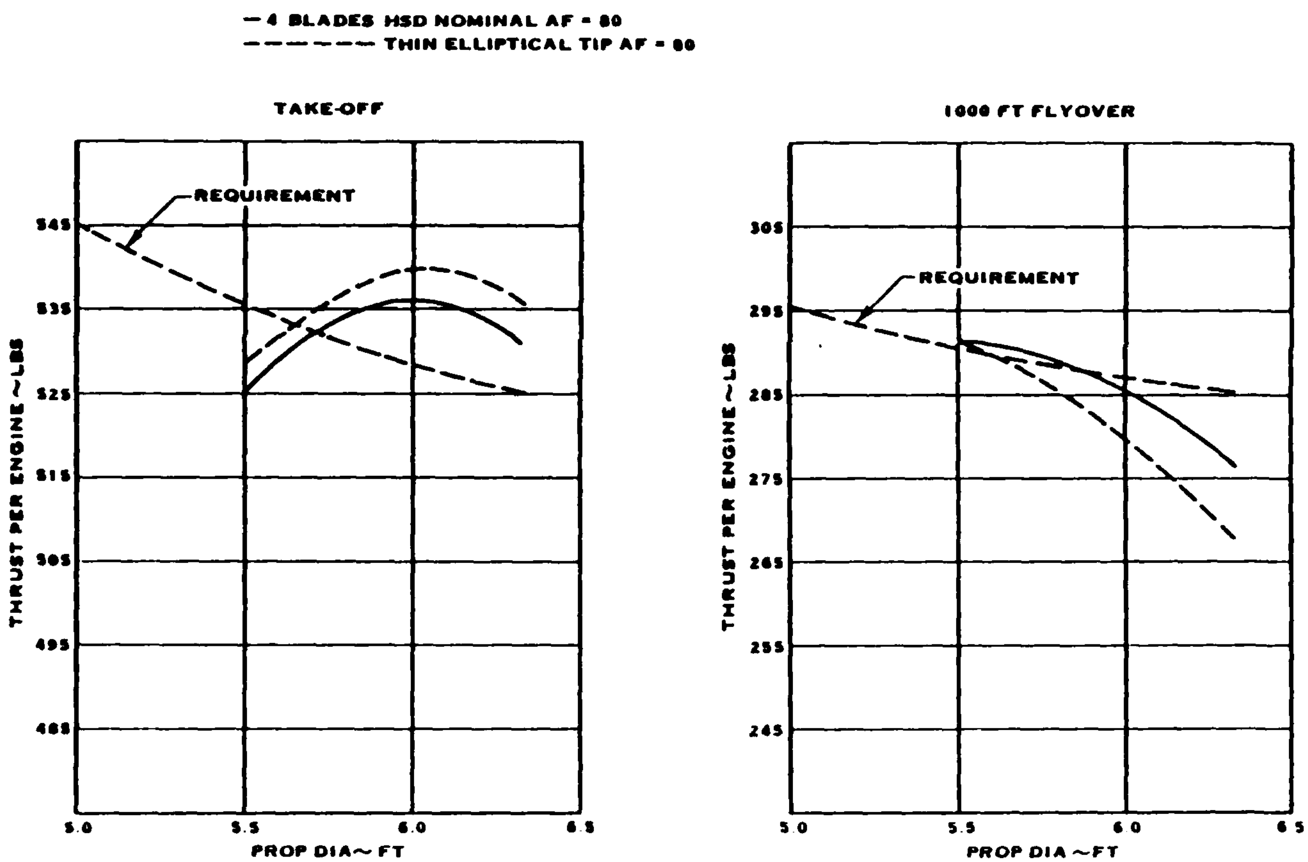


FIGURE 36. BEECH 76 DUCHESS PERFORMANCE REQUIREMENTS VS. DIAMETER

DISCUSSION

Study of Heavy Twin Engine Aircraft

The DHC-6 Twin Otter was selected as the reference aircraft for the heavy twin engine aircraft category. The Twin Otter was selected because of the availability of flyover data for verification of the noise prediction methodology. The Twin Otter also represents an aircraft designed in the time interval between the Debonair and Duchess aircraft and should, therefore, represent a degree of noise control between their respective levels. Based on the Debonair and Duchess studies, the Twin Otter should represent General Aviation aircraft with an average level of noise control.

The low noise approach of tip chord reduction, tip thickness reduction, optimized performance (to reduce diameter) and addition of more blades to obtain the maximum diameter reduction was applied to designing low noise replacement propellers for the Twin Otter. Based on the above design approaches, a total of six replacement propellers were evaluated for the Twin Otter. Figure 37 summarizes the noise levels, weight and cost for the Twin Otter and replacement propellers. Details of the configurations of Figure 37 are presented in Table IV. As for the Debonair and Duchess, levels of combined engine and propeller noise were estimated. Estimates of the turbo shaft engine noise level for the Twin Otter were obtained from an unpublished Hamilton Standard analysis of Twin Otter flyover noise. Figure 38, which shows the estimated combined engine and propeller noise levels for the Twin Otter propeller configurations, was used to evaluate the impact of propeller noise reduction upon overall aircraft flyover noise level.

Configurations 2, 3, and 5 of Figure 37 are the three blade replacement propellers for the Twin Otter. As shown by Figure 37, configuration 4 provided the largest reduction in propeller noise level of the three blade propellers, 3.2 dBA, with 17% reductions in weight and cost. The configuration 4 planform shown in Figure 39 was based on a quiet propeller by Hamilton Standard designed for the North American Rockwell OV10 several years ago. Configuration 4 showed an estimated 3.1 dBA reduction in combined engine and propeller noise, as shown in Figure 38. The 3.2 dBA noise reduction of configuration 4 was achieved by a substantial reduction in tip chord as indicated by the geometry comparison in Figures 39 and 40. As shown in Figure 40, the Twin Otter propeller had a small tip thickness ratio (below 0.03) so that no reduction in this parameter was possible for the replacement propellers.

Performance differences between the Twin Otter and configuration 4 OV10 replacement propeller were insignificant so no diameter reduction was possible. As shown in Figure 41, the mid and high frequency noise of configuration 4 causes the reduction in A weighted level relative to the reference Twin Otter propeller. Figure 42 shows that the reduction is due to a reduction in thickness and quadrupole noise.

As in the Debonair and Duchess studies, Figure 43 shows that diameter can be reduced if performance of the replacement blade design is better than the reference blade. Configuration 3 of Figure 37 is an elliptical tip performance optimized reduced diameter design which shows a 2.8 dBA reduction

Figure 44 shows that reduced diameter propellers with 4 and 5 blades can be designed to meet the performance requirements. Configurations 5 and 6 of Figure 37 are four blade designs. Configuration 7 of Figure 37 is a five blade design. Configuration 6 showed the largest propeller noise reduction for a four blade replacement propeller, 5.5 dBA. The 5.5 dBA reduction was due to a reduction in tip chord for the elliptical tip blade used in configuration 6, as shown by the planform comparison in Figure 39, and a 0.4 foot diameter reduction. The large reduction in tip chord for configuration 6 was partially offset by extremely low thickness ratio level distribution of the Twin Otter propeller as shown by the geometry comparison in Figure 40. The improved performance gained by use of a four rather than a three-bladed propeller was traded off for a 0.4 foot diameter reduction as shown by the four blade performance-diameter characteristics presented in Figure 44. Configuration 6 achieved a 5.5 dBA propeller noise reduction with a 16% weight reduction and 2% cost reduction. Configuration 6, which is a four blade propeller, shows weight and cost reductions are a result of the narrower blade used in configuration 6 which offset the addition of a blade. Since configuration 7 showed a substantial cost increase, configuration 6 is the category 2 replacement propeller for the Twin Otter.

Configuration 7 is a five blade replacement propeller that satisfies the Twin Otter performance requirement. However, the estimated diameter reduction, shown on Figure 44, is not significantly greater than that of the best four blade propeller, configuration 6. The addition of another blade does not show a significant noise reduction, 0.4 dBA, as shown in Figure 37. Configuration 6 was, therefore, selected as the category 3 replacement propeller consistent with the category definitions established.

From Figure 38, the impact of propeller noise reduction on the combined engine and propeller noise can be seen. For all configurations, the estimated engine and propeller noise continues to decrease with reduced propeller noise at almost a one to one ratio because the turbine engine noise level of the Twin Otter is low. The engine noise "floor" which was reached in noise reduction studies of the Debonair and Duchess were not reached for the Twin Otter.

The first and second noise reduction goal was achieved with configuration 6, a four blade, thin elliptical tip, reduced diameter propeller. A 5.5 dBA reduction in propeller noise with a 16% weight reduction and a 2% cost reduction was estimated for this configuration. Combined propeller and engine noise was reduced by 5.1 dBA by this design.

The maximum propeller noise reduction of 5.9 dBA was achieved with configuration 7, a five blade thin nominal tip reduced diameter propeller. A 26% increase in cost and 0.4% weight reduction were estimated for this configuration. Combined propeller and engine noise was reduced by 5.5 dBA for this design. Since the noise reduction for configuration 6 was within $\pm$ .5 of that for configuration 7, configuration 6 (because of its estimated cost reduction) was selected as achieving the third noise goal as per the guide lines previously established.

The Twin Otter propeller noise level was found to be thickness noise dominated. Applying the low noise approaches of narrow chord, thin tip, reduced diameter, and optimized propellers, a three blade propeller configuration was found that provided a 3.1 dBA reduction in propeller and engine flyover noise level. A four blade propeller provided a 5.1 dBA reduction in combined propeller and engine noise level. Both configurations provided reductions in weight and cost which were due to the large reduction in activity factor relative to the

Twin Otter propeller. No reduction in engine noise level was found necessary to achieve a 5 dBA reduction in flyover noise.

TABLE IV

HEAVY TWIN TWIN OTTER PROPELLER CONFIGURATIONS

CONFIGU-RATION	NO. OF BLADES	PROPELLER DIAMETER FT	AIRFOIL SERIES	ACTIVITY FACTOR	b/D@ .75r	b/D @ .99 r	h/b@ .75 .75 r	h/b @ TIP	CL @ .75 r
1	3	8.5	CLARK-Y	114.6	.077	.065	.048	.024	.366
2	3	8.5	16	89.8	.070	.022	.058	.032	.525
3	3	8.35	16	89.8	.070	.022	.058	.032	.561
4	3	8.5	16	90	.068	.034	.049	.030	.613
5	4	8.1	16	80	.059	.023	.074	.048	.561
6	4	8.1	16	80	.063	.020	.061	.034	.532
7	5	8.0	16	80	.059	.023	.074	.048	.480

TABLE IV (Cont'd)

CL @ TIP	SWEEP ANGLE @ TIP DEGREES	TIP HELICAL MN	DESIGN CL_i	TIP SHAPE
.150	0^o	.86	.50	---
.395	0^o	.86	.51	Elliptical
.437	0^o	.85	.51	Elliptical
.006	0^o	.86	.51	OV-10
.195	0^o	.83	.51	Nominal
.422	0^o	.83	.51	Elliptical
.135	0^o	.82	.40	Nominal

CONFIGURATION	1	2	3	4	5	6	7
DIAMETER (FT)	8.5	8.5	8.35	8.5	8.1	8.1	8.0
NO. BLADES	3	3	3	3	4	4	5
AIRFOIL	CL	16	16	16	16	16	16
TIP LOADING	N	N	N	N	N	N	N
TIP SHAPE	N	E	E	OV10	N	E	N
TIP THICKNESS	TO	TH	TH	TH	TH	TH	TH
ACTIVITY FACTOR	114.6	89.8	89.8	90	80	80	80

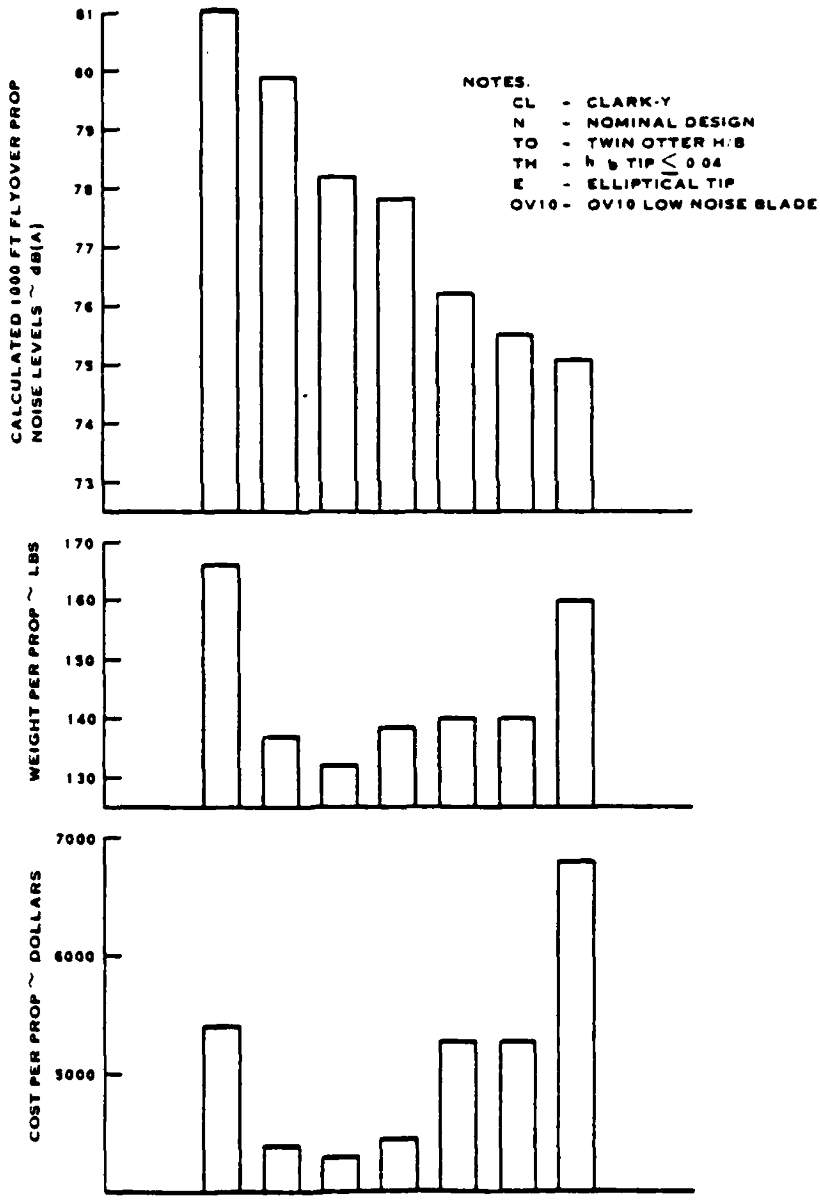


FIGURE 37. HEAVY TWIN ENGINE TWIN OTTER SUMMARY

CONFIGURATION	1	2	3	4	5	6	7
DIAMETER (FT)	8.5	8.5	8.35	8.5	8.1	8.1	8.0
NO. BLADES	3	3	3	3	4	4	5
AIRFOIL	CL	16	16	16	16	16	16
TIP LOADING	N	N	N	N	N	N	N
TIP SHAPE	N	E	E	OV10	N	E	N
TIP THICKNESS	TO	TH	TH	TH	TH	TH	TH
ACTIVITY FACTOR	114.6	89.8	89.8	90	80	80	80

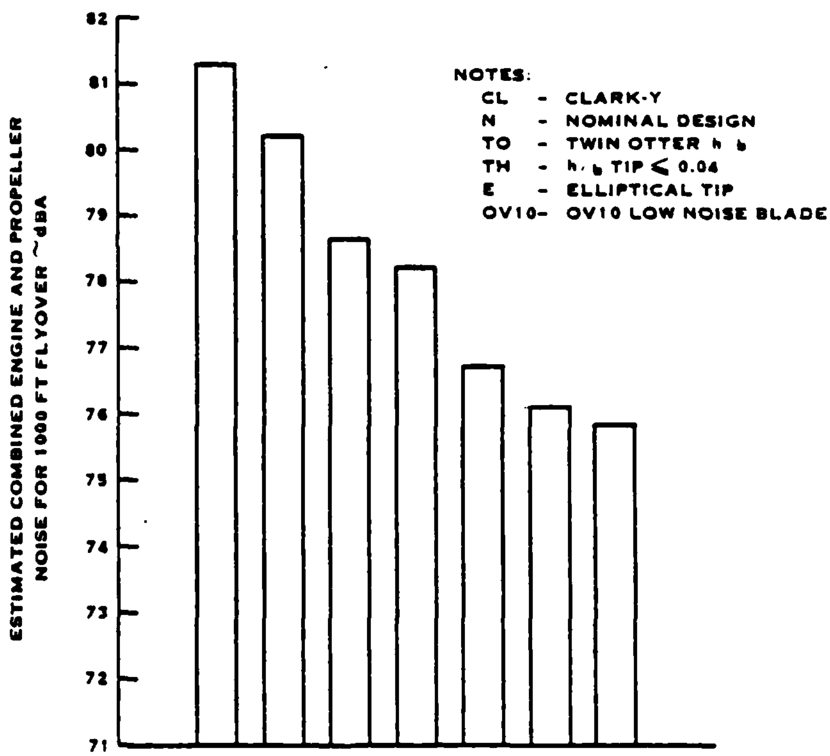


FIGURE 38. ESTIMATED COMBINED PROPELLER AND ENGINE NOISE FOR DHC-6 TWIN OTTER

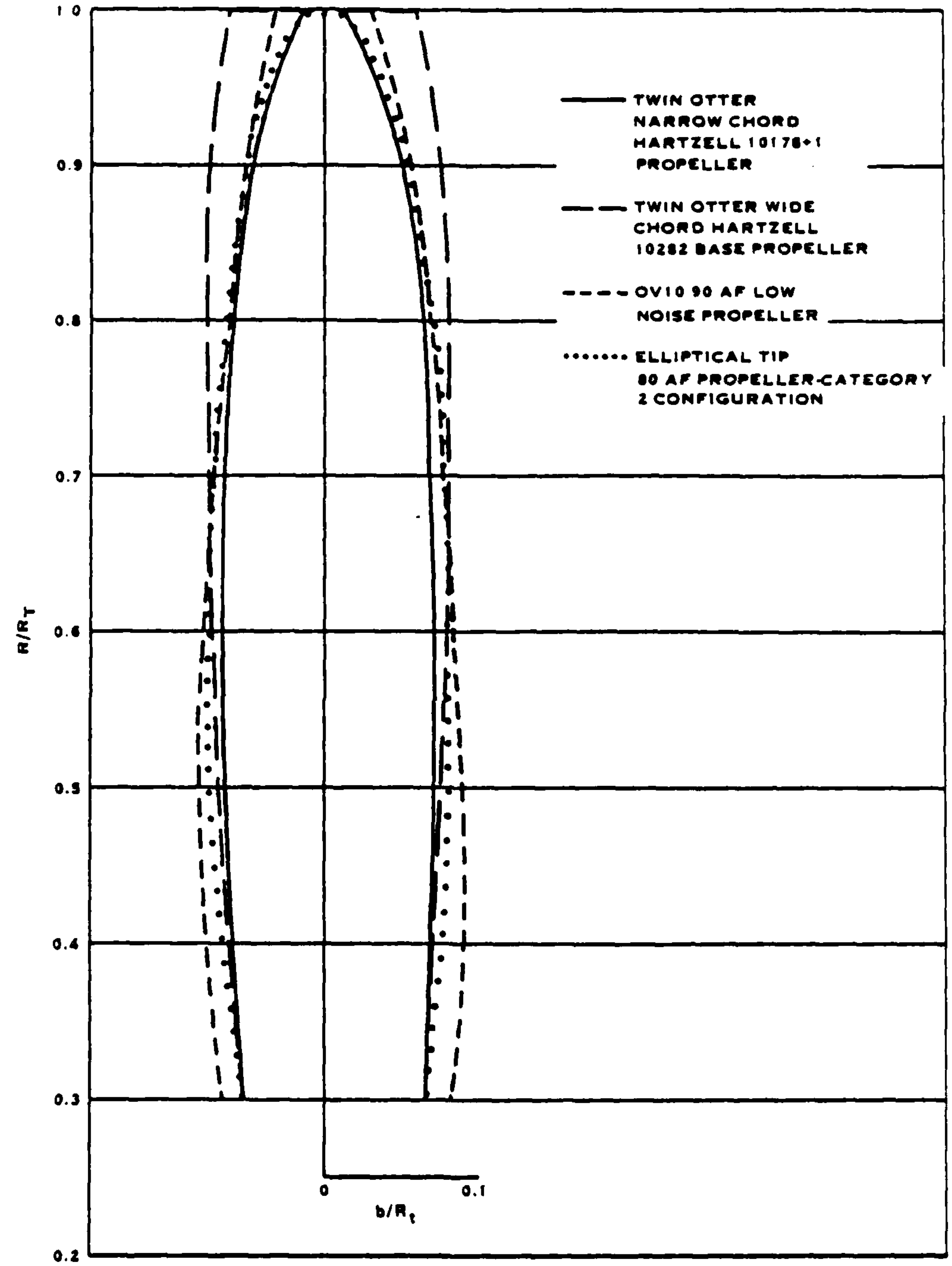


FIGURE 39. TWIN OTTER PROPELLER PLANFORMS

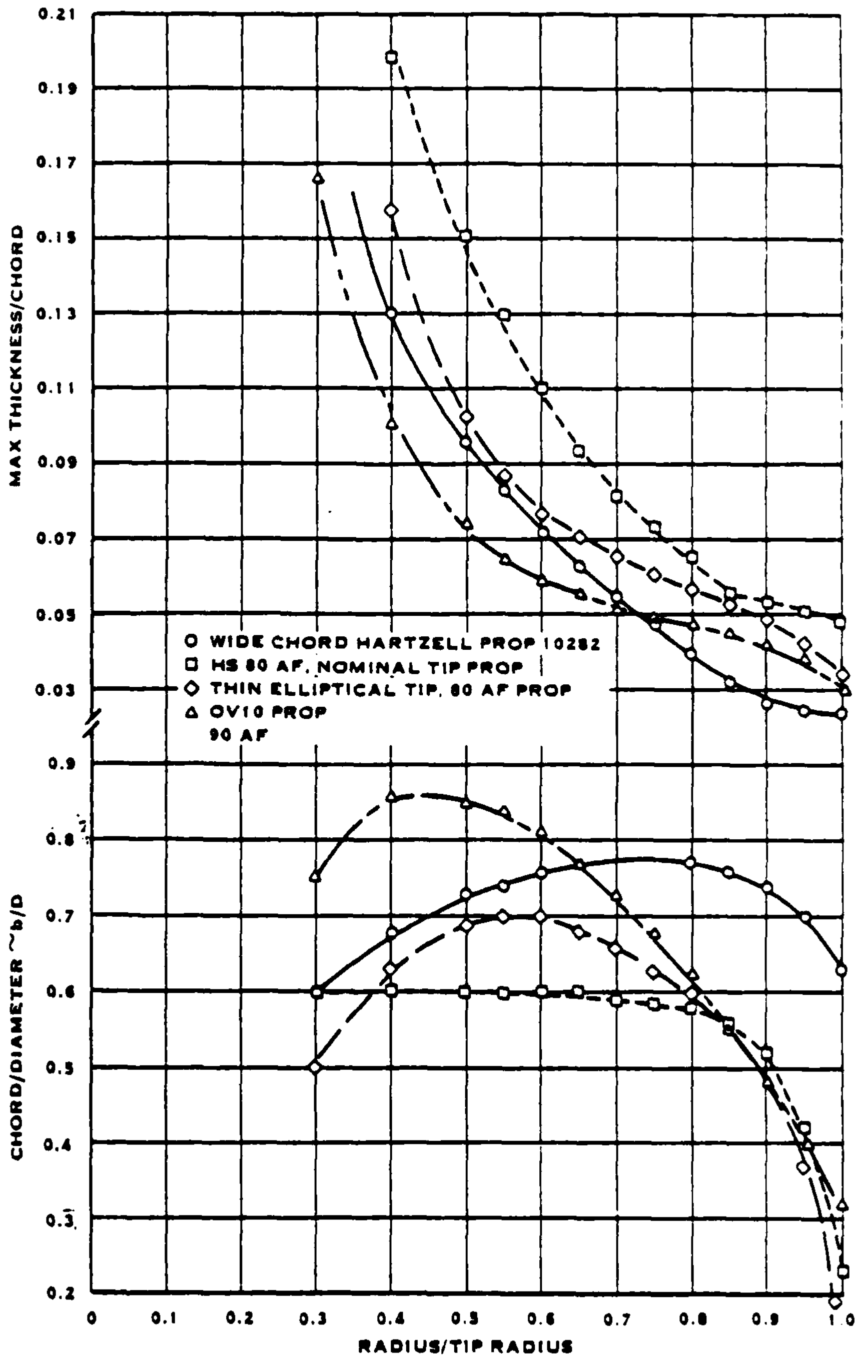
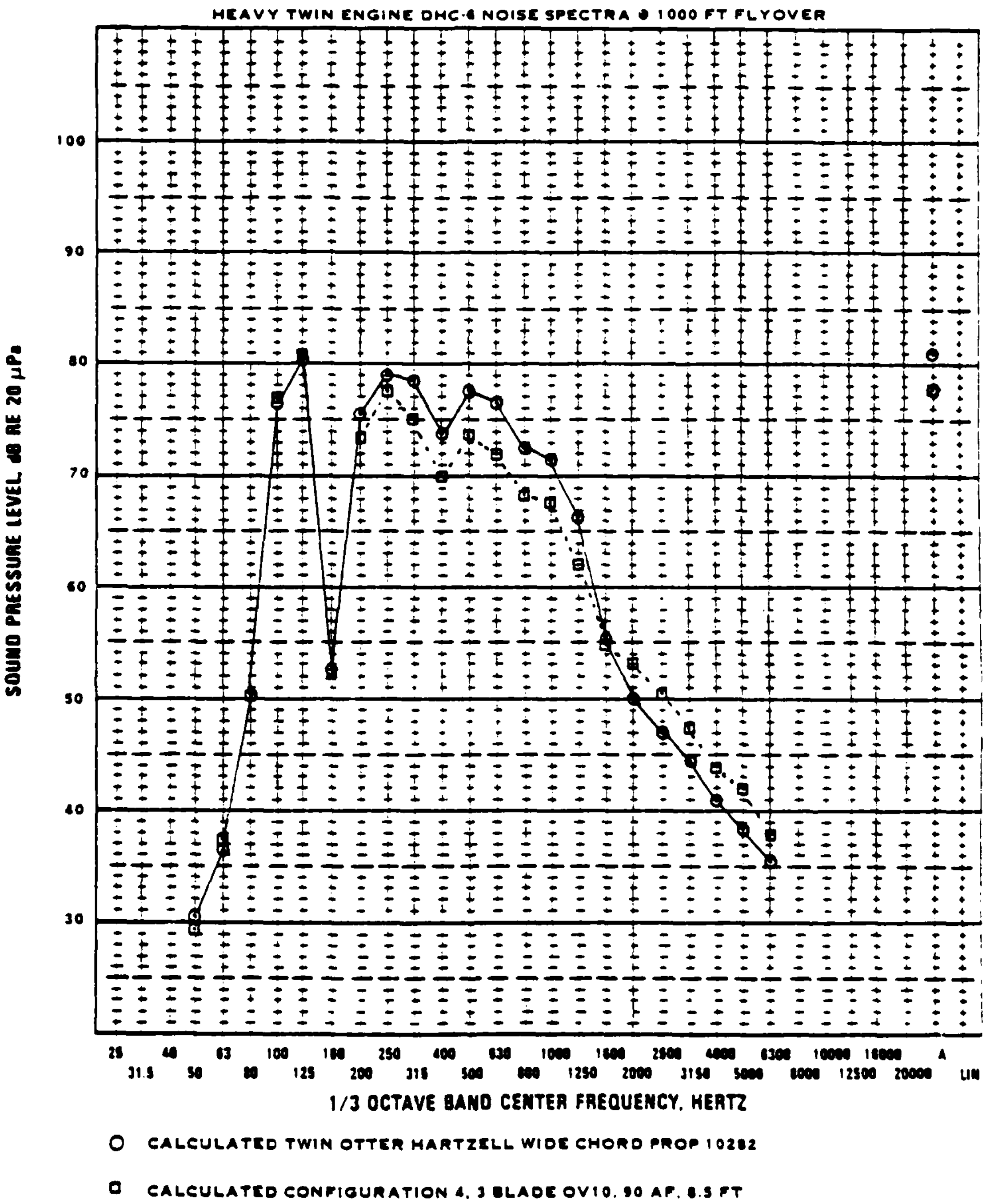


FIGURE 40. TWIN OTTER GEOMETRY COMPARISON



ONE THIRD
OCTAVE BAND
ANALYSIS

FIGURE 41. TWIN OTTER FLYOVER NOISE SPECTRA

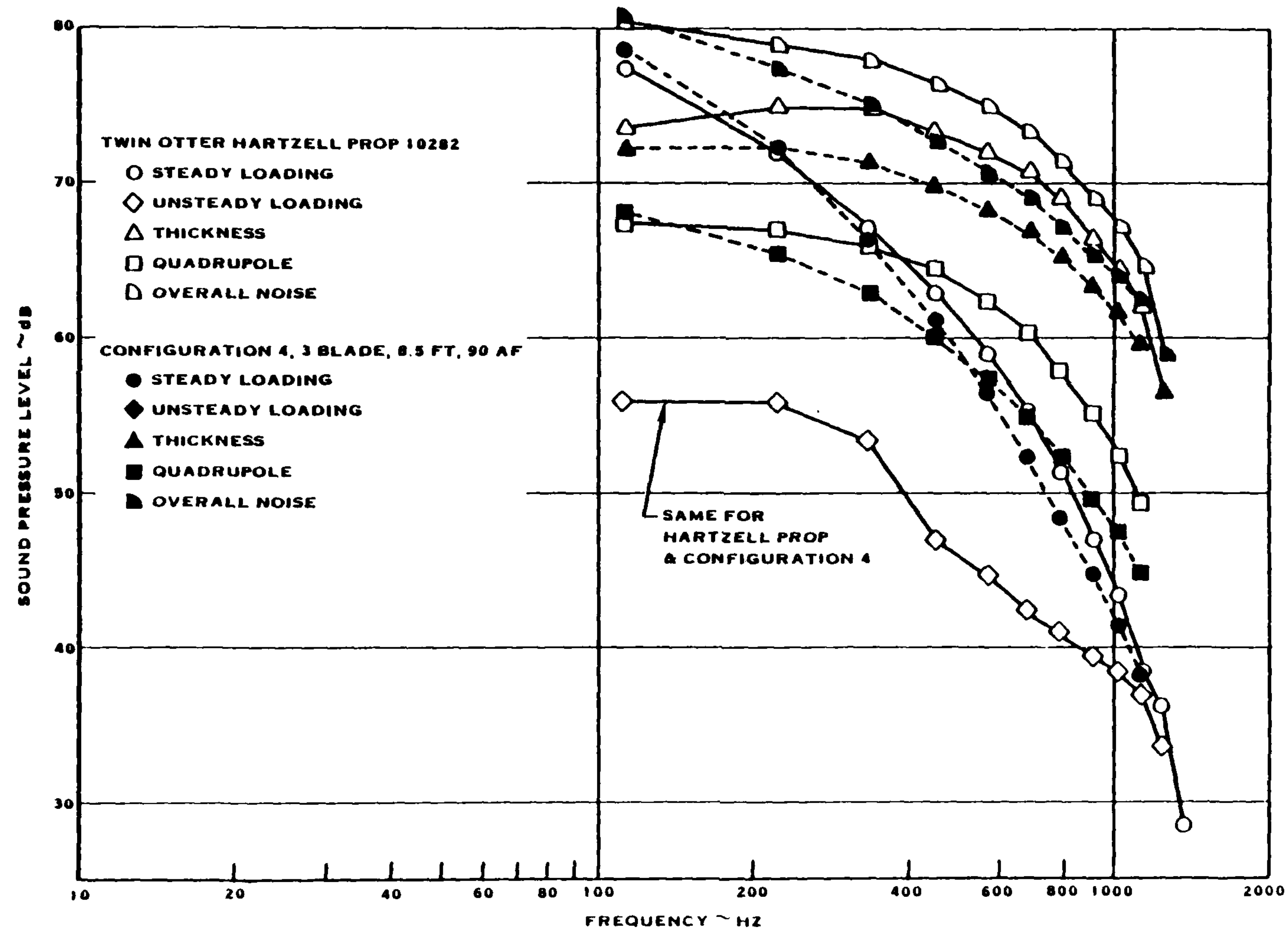


FIGURE 42. TWIN OTTER NOISE COMPONENTS

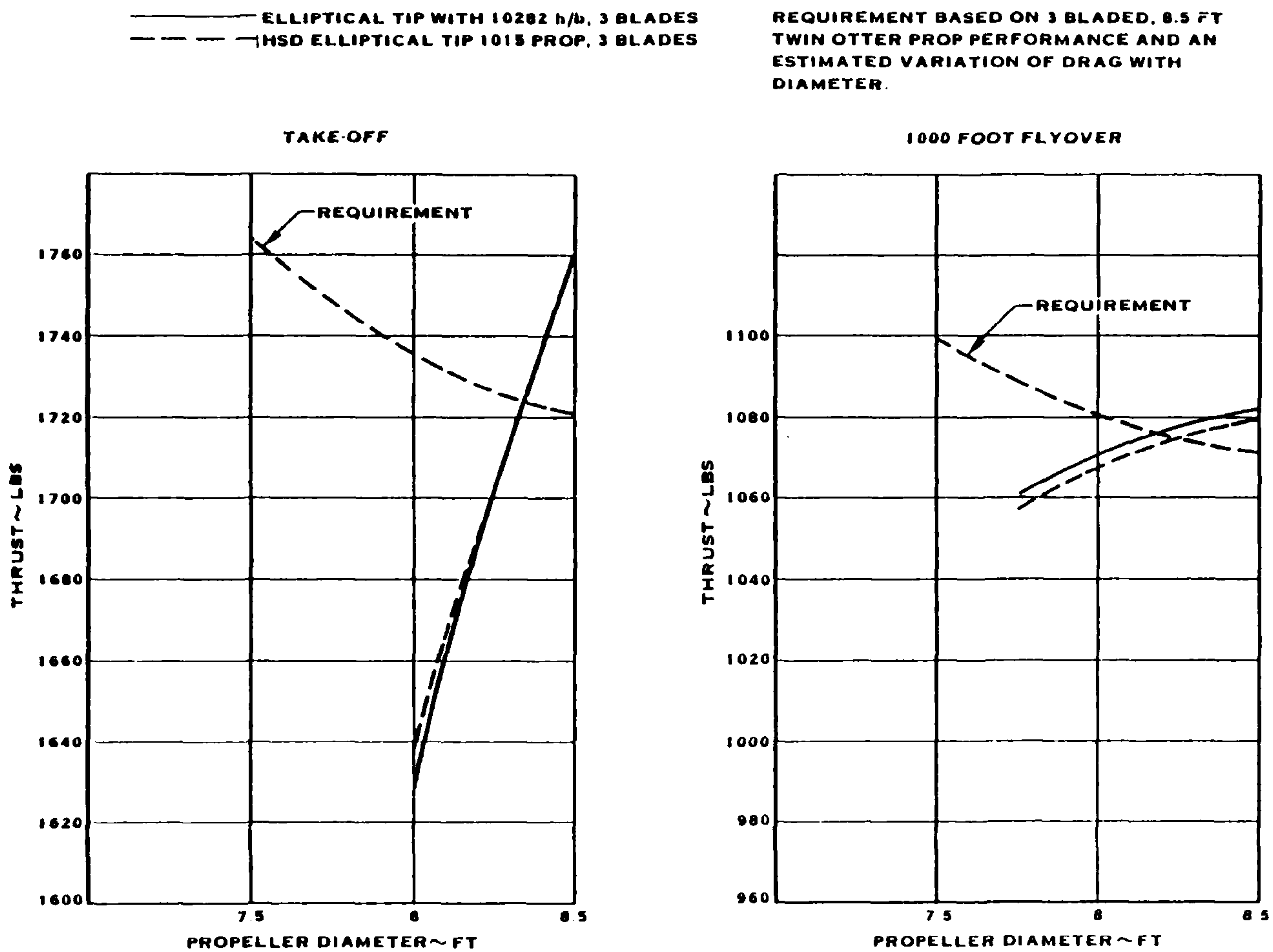


FIGURE 43. TWIN OTTER PERFORMANCE REQUIREMENTS AS A FUNCTION OF PROPELLER DIAMETER

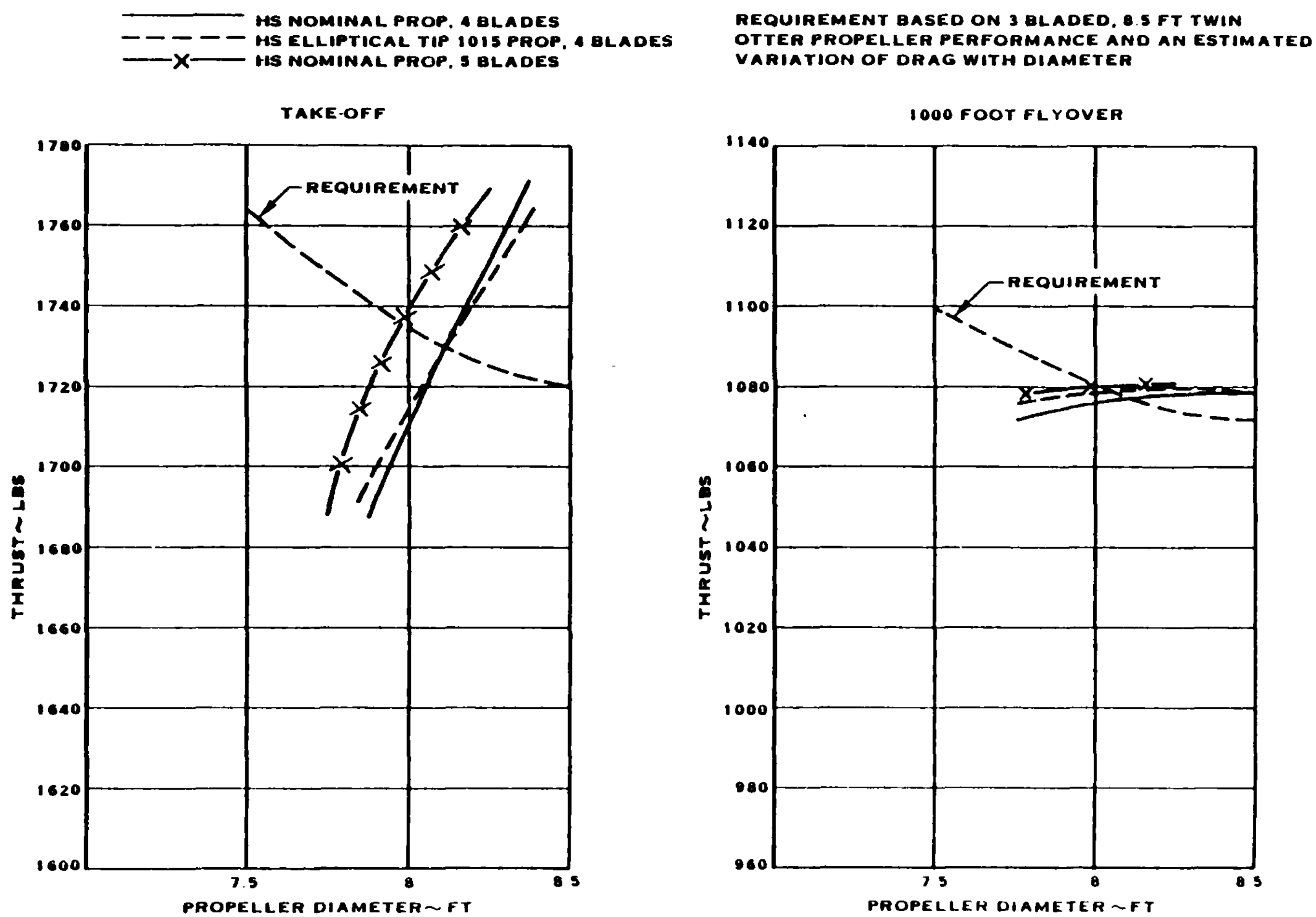


FIGURE 44. TWIN OTTER PERFORMANCE REQUIREMENTS AS A FUNCTION OF PROPELLER DIAMETER

CONCLUSIONS

The basic objective of the General Aviation noise trade off study was to define changes in weight and cost associated with noise reduction for three representative General Aviation aircraft in the single engine, light twin and heavy twin classes. The underlying assumption for the study was that General Aviation aircraft noise is dominated by propeller noise. While an in-depth engine noise evaluation was beyond the scope of the study, engine noise calculations made by use of existing methodology showed propeller noise to be the dominant factor in General Aviation aircraft. However, it was found that any substantial reductions in General Aviation aircraft noise would require suppression of existing engine noise.

The reader is also cautioned to consider that the noise reduction/cost/weight trade-offs obtained in this study are applicable only to the aircraft evaluated and not to the whole class of aircraft from which they were selected. Obviously, existing General Aviation aircraft represent a spectrum of airframe, engine, and propeller design technology which will result in a range of aircraft noise levels within each class. Conclusions are presented for the aircraft, not the aircraft category. Also structural adequacy of the low noise replacement propellers was considered in general but not evaluated in depth in the present study. Estimated noise reductions for the reference aircraft are believed to be attainable in structurally adequate blades but are considered only indications of the noise reduction potential for that aircraft category. In general, the noise of all existing propellers studied was thickness noise dominated. Therefore, the narrow, thin, elliptical tip configurations produced the best reductions with minimum impact on weight and cost. The dominance of thickness noise also prevented any substantial reductions by unloading the propeller tips. Reduced tip loading showed a reduction of 1 dB or less for the aircraft studied.

Three goals were established for the study: (1) The maximum noise reduction that can be achieved before engine noise suppression becomes necessary, (2) the noise reduction that can be achieved without weight or cost penalty, (3) the maximum noise reduction that can be achieved without an aircraft performance penalty.

The following conclusions were drawn from the study of the single engine Beechcraft 35-B33 Debonair:

1. The first and second goals were achieved with identical, 2 blade, thin elliptical tip propellers. This configuration showed an 11.1 dBA reduction in propeller noise with a 20% weight reduction and a 22% cost reduction. Propeller noise reductions beyond this level included weight and cost penalties and approached the estimated engine noise level.

2. The third goal, maximum propeller noise reduction, was achieved with a straight blade 3-blade, thin, elliptical tip propeller configuration which provided a 13.7 dBA reduction in propeller noise with a 3% weight reduction but a 24% cost penalty. At this level of propeller noise reduction, the engine noise was estimated to be a significant factor in the overall noise level.

3. Blade sweep was effective for achieving reduced noise of the Debonair but blades with sweep sufficient to produce substantial noise reductions require structural design and cost studies to define potential weight and cost penalties. If sweep is limited, then other straight blade designs show similar noise reduction benefits.

The following conclusions were drawn from a study of the Light Twin Beechcraft Duchess 76:

1. The first and second goals were achieved with identical, 2 blade, thin elliptical tip propellers. This configuration showed a 3.8 dBA reduction in propeller noise level with a 13% weight reduction and a 12% cost reduction. Propeller noise reductions beyond this level included weight and cost penalties and approached the estimated engine noise level.

2. The third goal was achieved with a 4-blade, thin, elliptical tip propeller which provided an 8.6 dBA reduction in propeller noise with a 13% weight penalty and a 59% cost penalty.

The following conclusions were drawn from a study of the Heavy Twin DHC-6 Twin Otter:

1. For the Twin Otter, all of the noise reduction goals were achieved with identical propeller configurations, a 4-blade, thin, elliptical tip propeller. This configuration showed a reduction in propeller noise level of 5.5 dBA with a 16% weight reduction and a 2% cost reduction.

From the above conclusions, it appears that the most productive currently available approaches to reduce noise levels of General Aviation propellers are to:

1) Use an elliptical tip shape
2) Use the smallest tip airfoil thickness consistent with structural integrity and manufacturing technology
3) Optimize propeller performance to reduce diameter to the minimum required for acceptable aircraft performance
4) Use the largest number of blades consistent with performance requirements, weight, and cost.

The noise reduction obtainable with revised propeller design varies greatly. On the newer aircraft, such as the Beech Duchess, the reduction will probably be smaller than for older aircraft, such as the Beech Debonair.

RECOMMENDATIONS

An ability to reduce noise of General Aviation Aircraft by replacing their propellers is indicated by studies summarized in this report. The noise reduction potential was found to be a strong function of the existing propeller design for the particular aircraft. The problem still remains to relate the results for 3 aircraft of the current study to the wide spectrum of existing General Aviation aircraft. Therefore, the following recommendations are made:

1. One of the most important concepts in reducing the level of propeller noise was the design of propellers with thin-narrow chord tips to reduce the thickness related noise level. The scope of the present study did not permit in-depth evaluation of the structural and life limits associated with thinning propeller tips. Therefore, such an evaluation is recommended.

2. Since the RAF-6 and Clark Y airfoils of the existing propellers studied did not appear to perform as well as the NACA Series 16 airfoils used in the quiet replacements, it is recommended that experiments be performed to verify that performance can be improved and therefore noise reduced by reduction of propeller diameter (tip speed).

3. Analytical and experimental work is recommended to establish the noise reduction potential of tip modifications including bent tip, winglets or tip plates. Performance of such modifications must be established in these studies. If good performance/noise trade offs are found for such modifications, then cost and weight evaluations should be conducted.

4. There is an apparent noise benefit for swept blade General Aviation propellers which was not utilized in this study because the structural design, weight, and cost studies required were beyond the scope of the contract. Blade sweep appears to be the next step in noise reduction technology, if noise reductions greater than those found in this study are required. It is therefore recommended that such studies be conducted.

5. Establish a simplified system to correlate General Aviation aircraft flyover noise with propeller design and operating parameters. This method could be used to evaluate the noise reduction potential of the current General Aviation Fleet. This would greatly facilitate in bracketing the flyover noise envelope for existing General Aviation aircraft, identifying the current level of propeller design technology for General Aviation aircraft, and would provide a tool for comprehensive application of the low noise propeller design approaches developed in this report.

APPENDIX A

NOISE PREDICTION METHODOLOGY

Appendix A
Noise Prediction Methodology

The noise prediction methodology used in the General Aviation Propeller Study makes use of the latest methods for predicting tone noise components and existing methods used for many years for prediction of broad band noise components.

Noise produced by a propeller consists of several components which must be summed to predict total noise. The components which result in the characteristic tone noise components of a propeller at harmonics of blade passage frequency $\left(\frac{\text{RPM} \times \text{number of blades} \times \text{an integer}}{60}\right)$ are monopole (thickness) noise, dipole (steady loading) noise, unsteady loading noise and nonlinear (quadrupole) noise. Thickness noise is a function of the chord and thickness of the airfoils making up a propeller blade. Steady loading noise is a function of the pressure loading distribution on the surface of a propeller blade. Unsteady loading noise is primarily caused by flow disturbances such as atmospheric turbulence and ground vortices and is generally low in level at flight conditions. Quadrupole noise is caused by the disturbances in the air surrounding the propeller blades which is generally important at higher tip speeds for the thicker and more highly loaded blades.

In addition to tone noise components, a broad band propeller noise component is also part of the propeller noise operation. In flight, this noise component is believed to be associated with vortex shedding from the trailing edges of the propeller blades.

The theory used for predictions of tone noise in the General Aviation Propeller Study was first developed in 1976 (ref. 1). This theory was developed primarily for prediction of near field noise (at locations within one propeller diameter) of advanced propellers (Prop-Fans) operating at high subsonic speed. This work was based on the Ffowcs-Williams Hawkings "acoustic analogy" in which the equations of fluid motion are cast into a wave equation for acoustic pressure. Two components of noise are calculated in the theory: (1) monopole (thickness) noise; and (2) dipole (loading) noise. A third, second order term in the Ffowcs-Williams Hawkings equation (the quadrupole source term) was ignored in this early theoretical development because it was believed to be small relative to the monopole thickness term. In the formulation of this theory, Hanson assumed that the propeller blades travel along helical surfaces defined by the forward flight speed of the aircraft and the angular velocity of the propeller. This method does not treat the nonlinear quadrupole source. Of course, the lack of the quadrupole source should not be surprising as none of the propeller and rotor noise prediction procedures which existed in 1976 had ever included this source. This method is a time domain method, i.e., the acoustic pressure wave form generated by blade is calculated and then the frequency spectrum of the noise is obtained by Fourier analysis.

The basic output of the program which incorporates the time domain method is the acoustic pressure waveform at a specified point in space assumed to be moving forward at the same speed as the propeller. The harmonic components of noise obtained from a Fourier analysis of this waveform are also an output. Thus, it is possible to calculate the noise at the location of a fuselage near a propeller as the aircraft is flying at cruise speed.

In 1977, a Frequency Domain Method was developed for predicting Prop-Fan noise. This Frequency Domain Method offered several advantages over the Time Domain Method. First, in order to calculate the noise of a swept blade at supersonic tip speed, the computation time of the Time Domain Method is high because the acoustic pressure waveform must be accurately defined. Unless the span of the blade is divided into very small strips near the point where the flow over the blade reaches Mach 1, substantial numerical noise is generated in the numerical differentiation procedure. This results in an unacceptable error in the acoustic pressure waveform generated by the program.

Second, in the Time Domain Method the acoustic pressure waveform of the blade must be calculated precisely if accurate levels of blade passage frequency harmonics are to be generated by Fourier analysis of the waveform.

Late in 1977 Hanson developed a quadrupole prediction theory and was able to show at the end of 1977, by use of a simplified nonlifting aerodynamic model, that the quadrupole noise is an important noise source in Prop-Fans with unswept or slightly swept blades operating at transonic tip speeds (ref. 2). The addition of the quadrupole component to the linear monopole and dipole components calculated by the Frequency Domain Method was shown to improve the correlation with Prop-Fan acoustic test data.

Throughout 1978, the major Prop-Fan Methodology development consisted of establishing a working procedure for including the quadrupole component in the Prop-Fan Acoustic Design Procedure.

Early in 1979, a far field version of Frequency Domain Method was combined with the portions of the existing Hamilton Standard Propeller Noise Prediction Procedure to allow calculations of far field noise at the takeoff and landing conditions required for certification of large propeller aircraft and at the high speed flyover conditions required for certification of small propeller aircraft. This combined method includes the broad band noise and unsteady loading noise prediction procedures from the previous Hamilton Standard Propeller Noise Prediction Procedure. Also the routines for calculating Perceived Noise Level (PNL), Tone Corrected Perceived Noise Level (PNLT), Effective Perceived Noise Level (EPNL) and A-Weighted Sound Pressure Level (in dBA) which were included in the previous Hamilton Standard Propeller Noise Prediction Procedure are included in the new combined program.

In contrast to the earlier procedure, the non-compact or distributed character of the noise generated by the blades can be accurately calculated by the new method. Also, in the new method, the blades are placed on the helical surface swept out by the blades as they advance through the air. Of most importance for advanced propellers, the new method handles the effect of blade sweep. Sweep has been used in Prop-Fan designs to reduce near field noise at high speed cruise conditions. This sweep optimization utilized the concept of destructive interference of noise from different spanwise stations of the Prop-Fan blade. This concept is based on the fundamental assumption of linear acoustics that the acoustic pressure at any observer position can be calculated as the sum of contributions from each element of the source volume and surface area. To be done correctly, the summation (or integration) process must account for the amplitude and phase of the elemental contributions. If source dimensions of the blades are greater than about 1/2 the wavelength of interest (i.e., if the source is "acoustically non-compact"), then at some observer positions, elemental signals from different portions of the source will arrive out of phase. The net noise will then be reduced by self-interference below the level which would be obtained if the source dimension were very small ("acoustically compact"). Although the term "acoustically non-compact" is relatively new, the principle has been known for many years. For example, in Gutin's original theory for propeller noise, the appearance of Bessel functions and the polar directivity pattern result from phase variation around the propeller circumference. For most conventional propellers, chordwise and spanwise phase variations can be neglected at blade passing frequency (number of blades times rotation speed). However, for the Prop-Fan, the combination of high Mach number, many blades, and large chord require that chordwise and spanwise phase variations be included.

The phase interference concept is most clearly illustrated with reference to the effect of sweeping a blade planform as suggested by Fig. 1A. At blade passing frequency, the noise from any strip of the blade is simply a sinusoidal wave with an amplitude and phase angle. The noise from one propeller blade is simply the vector sum of the contributions from each strip and the noise of the total propeller is the product of the vector sum and the number of blades. The effect of sweeping the tip back is to cause the signal from the tip to lag (increased phase angle) the signal from the mid-blade region, thus causing partial interference and reduction in net noise.

In the methods developed for design of Prop-Fans and incorporated in the far field noise prediction procedure used for the General Aviation Propeller Study, a graphical version of the concept discussed above has been included. In this graphical procedure the strip noise contributions are treated as vectors in the complex plane having amplitude and phase angle. Then, the summation of the contributions from the strips is performed by adding the vectors head-to-tail, as shown at the right of Fig. 1A. It can be seen that a lack of variation in phase angle in the individual contributions from several spanwise locations on the blade would vectorially add up to a value no different from the total length of the vectors (analogous to the resultant noise.) This is the general result for unswept and slightly swept blades. However, by varying the amplitude and phase of the noise produced by the various spanwise stations on the blade, reductions in the resultant amplitude can be achieved, as shown in the phase plot at the right of Fig. 1A. This is the result for a Prop-Fan blade at cruise conditions with substantial blade sweep. At takeoff conditions in the far field, the reductions in noise due to sweep are less, particularly at lower harmonics of blade passage frequency. However, worthwhile reductions at higher frequency harmonics important in General Aviation noise certification do result from blade sweep.

In summary, the new far field Propeller Noise Prediction Method which has been used for the general Aviation Propeller Study is a powerful new tool for propeller noise analysis. In contrast to earlier methodology, it incorporates all important tone and broad band noise components and is capable of analyzing the effects on noise generation of planform (including sweep) and airfoil changes.

References

1. D.B. Hanson, "Near Field Noise of High Speed Propellers in Forward Flight," AIAA Paper No. 76-505, 1976.

2. D.B. Hanson and M.R. Fink, "The Importance of Quadrupole Sources in Prediction of High Speed Propeller Noise," J. Sound and Vibration, Vol. 62, No. 1, 1979.

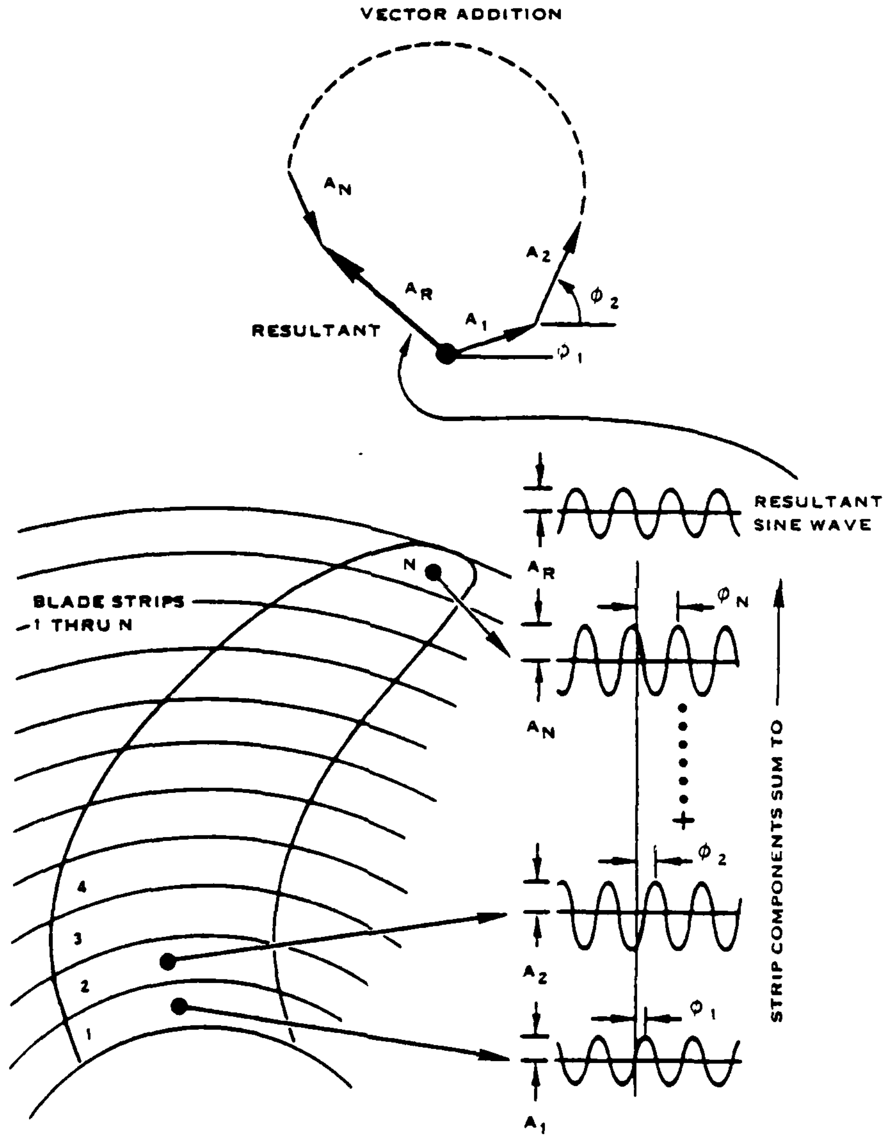


FIGURE 1A. ACOUSTIC STRIP ANALYSIS CONCEPT

APPENDIX B

PERFORMANCE PREDICTION METHODOLOGY

PERFORMANCE PREDICTION METHODOLOGY

The aerodynamic analysis included in this General Aviation propeller study was based on the well proven Hamilton Standard Propeller Performance Method. This method has been used for the design and performance prediction of all propeller designs produced by Hamilton Standard in the past few decades. This vortex theory was derived from the work of Goldstein (ref. 1) and Locke (ref. 2). Goldstein obtained the exact closed solution for the induced flow field around an optimum, lightly loaded propeller with a finite number of blades. His wake model was defined as a rigid helicoid moving at a constant displacement velocity. Locke then combined Goldstein's solution to the radial distribution of induced velocities with the propeller vortex theory to formulate an accurate propeller design and performance theory including the axial and tangential components of induced velocity. Moreover, Locke established that the theory could be applied without the limiting assumptions of optimality and light loading.

The method utilizes two-dimensional, empirical airfoil data to compute the lift and drag distribution on a series of blade elements along the blade radius. This is accomplished by an iteration process at each radial element between the lift established by the induction analysis and by the empirical 2-D airfoil data. The corresponding spanwise thrust and torque loadings are then calculated from the vector resolution of the lift and drag forces and then integrated to define the propeller efficiency at the operating velocity.

The Hamilton Standard Propeller Performance Method developed from this basic theory has been continuously improved over the years and has been correlated with wind tunnel test data on many different propeller configurations ranging from small models to full scale propellers tested in wind tunnels of various sizes and types. Moreover, the basic two-dimensional airfoil data packs have been built up with data from over 20 wind tunnel tests. About 100 airfoil sections representing six airfoil families have been tested over wide ranges of angle-of-attack, Reynold's numbers and Mach numbers. For each airfoil family, the test airfoils covered the ranges of thickness ratio and camber of interest for propeller blade design. Thus with these extensive data packs incorporated in the method, the aerodynamic performance for any propeller configuration may be accurately computed for the complete operating spectrum of interest.

Today, the method is programmed on the IBM 370 computer permitting nearly 250 performance points per minute to be computed. Thus the extensive propeller parametric design analysis and performance prediction required for this study may be accurately calculated in a short run time.

<u>References</u>

1. Goldstein, S., "On the Vortex Theory of Screw Propellers," Proceedings of the Royal Aeronautical Society, Series A, Vol. 123, 1929.

2. Locke, C.N.H., "Application of Goldstein's Airscrew Theory to Design," British ARC R&M No. 1377, November 1930.

APPENDIX C

WEIGHT PREDICTION METHODOLOGY

AD-A082 120 UNITED TECHNOLOGIES CORP WINDSOR LOCKS CONN HAMILTON --ETC F/G 1/3
INFLUENCE OF NOISE REDUCTION ON WEIGHT AND COST OF GENERAL AVIA--ETC(U)
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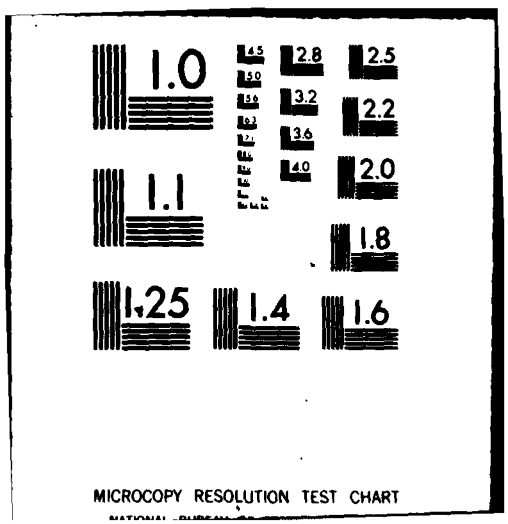
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MICROCOPY RESOLUTION TEST CHART

WEIGHT PREDICTION METHODOLOGY

The weight prediction method was based on an HSD 1971 study of General Aviation propellers (ref. 1) based on 1970 O.E.M. catalog single unit weights. The 1979 generalized weight equation was checked against propeller weight data. Using a 21 propeller sample, the weight from the generalized weight equation was compared to the actual weight. The results of this comparison are shown in Figure 1C which shows a ± 12% band for the weight estimates from the generalized weight equation. The generalized weight equation applies to 1978 General Aviation solid metal propeller manufacturing technology only. Conclusions and discussions of weight contained in the report are confined to 1978 solid metal propeller technology unless specifically stated otherwise. Table IC shows the 1978 generalized propeller weight equation.

Reference

1. Worobel, R. and Mayo, Millard G., "Advanced General Aviation Propeller Study," NASA CR114289, April 1971.

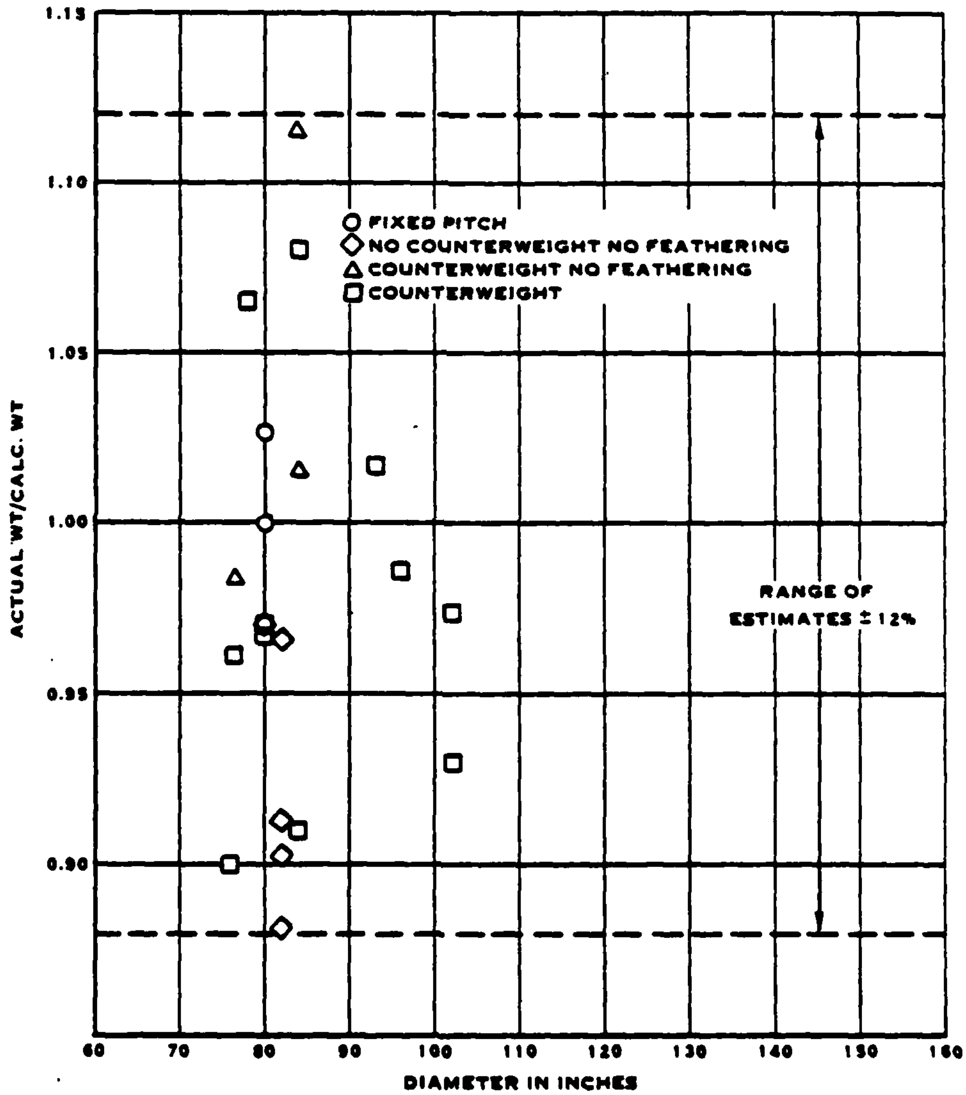

FIGURE 1C. EVALUATION OF ACCURACY OF WEIGHT ESTIMATING EQUATION

Table IC

Generalized Propeller Weight Equation
for
Aircraft Propellers Manufactured in 1978

$$W_T = K_W \left[\left(\frac{D}{10}\right)^2 \left(\frac{B}{4}\right)^{0.7} \left(\frac{A.F.}{100}\right)^u \left(\frac{ND}{20,000}\right)^v \left(\frac{SHP}{10D^2}\right)^{0.12} (M+1)^{0.5} \right] + C_W$$

Where:

W_T = Prop. Wet Weight, lbs. (excludes spinner, deicing & governor)

D = Prop. Dia, Ft.

B = No. of Blades

A.F. = Blade Activity Factor

N = Prop. Speed, RPM (take-off)

SHP = Shaft Horsepower, HP (take-off)

M = Mach No. (Design Condition: Max Power Cruise)

$C_W = y \left(\frac{D}{10}\right)^2 (B) \left(\frac{A.F.}{100}\right)^2 \left(\frac{20,000}{ND}\right)^{0.3}$ = Counterweight Wt., lbs.

K_W, u, v and y values for use in the above equations are found from table below:

Aircraft Class	1978 Technology		K_W	u	v	y
I Single Engine Fixed Gear	(1)	(1)	170	0.9	0.35	0
II Single Engine Retractable Gear	(2)	(2)	200	0.9	0.35	0
III Light Twins	(3)	(3)	220	0.7	0.40	5.0
IV Medium Twins	(3)					
V Heavy Twins	(3)					

Propeller types associated with above K_W are as follows:

(1) All fixed-pitch props

(2) Mc Cauley non-counterweighted, non-feathering, constant speed props

(3) All Hartzell, all Hamilton Standard small props, and feathering Mc Cauley

APPENDIX D

COST PREDICTION METHODOLOGY

COST PREDICTION METHODOLOGY

The basis for the propeller cost prediction method was also the cost generalization from the 1971 HSD General Aviation propeller study (ref. 1). To update the 1971 propeller cost generalization to the 1978 level single unit O.E.M. propeller cost per pound for 1978 were compared with the 1970 levels. Based on the comparison, a recommended generalized 1978 cost equation was derived. Since the single unit propeller cost is a function of yearly unit production, the generalized cost equation reflects only the 1978 rate of production. Evaluation of the impact of production rate upon propeller cost was considered beyond the scope of the present study. Table ID, attached, shows the 1978 generalized cost equation. The generalized cost equation reflects 1978 solid metal propeller technology. Conclusions and discussions of propeller cost contained in the report are based on 1978 solid metal propeller technology unless specifically stated otherwise.

References

1. Worobel, R. and Mayo, Millard G., "Advanced General Aviation Propeller Study," NASA CR114289, April 1971.

Table ID

Generalized Cost Equation For
General Aviation Aircraft Propellers Manufactured in 1978

$$C_1 = F\,(3B^{0.75} + E)$$

where:

C_1 = Single unit O.E.M. propeller cost \$/lb.

B = Number of blades

F = Single unit cost factor (see table below)

E = Empirical factor (see table below)

Category	F	E
I Single Engine Fixed Gear	7.56	1.0
II Single Engine Retractable Gear	5.99	1.5
III Light Twins	5.02	3.5
IV Medium Twins	4.08	3.5
V Heavy Twins	3.14	3.5

APPENDIX E

REQUIRED THRUST - PROPELLER DIAMETER METHODOLOGY

REQUIRED THRUST-PROPELLER DIAMETER DETERMINATION

One of the approaches to reducing propeller noise is to reduce propeller diameter and therefore reduce tip speed. However, as the propeller diameter is reduced, the slip stream velocity increases causing an increase in drag for the aircraft components bathed in the slip stream. Therefore, the thrust required to maintain a fixed level of aircraft performance increases as the propeller diameter is reduced. To define allowable reductions in propeller diameter, the effect of reduced diameter upon drag must be estimated.

For the General Aviation propeller noise study, a method based on information from references 1 and 2 was used to evaluate changes in drag with propeller diameter reductions. This method is outlined below:

Step 1 - The propeller thrust was assumed to be equal to the aircraft drag at a level flight cruise condition. Drag coefficients were estimated for the aircraft components from available information in technical literature sources, references 1 and 2.

Step 2 - The average slipstream velocity was estimated from performance calculations. Drag for the components in the slipstream was calculated using a q based on the slip stream velocity ($q_{ss} = \frac{1}{2} \rho \{V_{ss}\}^2$). The total aircraft drag was calculated from the sum of the aircraft component drags. Calculated aircraft drag was compared to the calculated propeller thrust. To obtain agreement of the calculated aircraft drag to within ± 3% of the calculated thrust, the aircraft component drag coefficients were varied within the range indicated by the literature until agreement is reached. This is the reference set of drag coefficients used to evaluate aircraft performance.

Step 3 - The propeller diameter was reduced and cruise propeller performance plus average slipstream velocity were calculated at an assumed thrust level. Based on the new slipstream velocity, a new aircraft drag was calculated. When the increase in assumed thrust level was equal to the increase in calculated drag, this point was considered to be the aircraft thrust requirement for the reduced propeller diameter. Thrust requirements for 3 or more propeller diameters were determined to define a thrust required versus propeller diameter curve for the cruise condition.

Step 4 - The same procedure as outlined in Steps 1-3 was used to define thrust required versus propeller diameter curves for the take-off and 1000 foot fly-over conditions. For these conditions, the wing drag coefficient was assumed to be represented by a parabolic polar approximation and a turbulent Reynolds number was assumed in order to scale the drag coefficient determined at the cruise condition to the new flight conditions. At take-off, where the aircraft thrust requirement is determined by the aerodynamic drag, resistance of rolling friction, and the thrust needed to accelerate the aircraft; only the aerodynamic drag was assumed to vary with propeller diameter.

In the following discussion, the influence of diameter reduction on propeller thrust required to maintain reference aircraft performance is discussed for the single engine, light twin, and heavy twin aircraft. These results are based on general procedures and assumptions described above.

<u>Single Engine Aircraft - Beech Debonair 35-B33</u>

For the single engine Debonair with a nose mounted engine, the total aircraft drag was broken into two components, the wing drag and a combined fuselage/engine installation drag. The wing drag coefficient was assumed to be equal to:

$C_{D_W} = C_{D_{WO}} + \frac{(CL)^2}{\pi A e}$ where the airplane efficiency factor, e, was assumed to be 0.9 and the effective aspect ratio for the Debonair was 6.07. Therefore:

$$C_{D_W} = C_{D_{WO}} + 0.0582\ (CL)^2$$

At the maximum cruise condition for the Debonair, $C_{D_{WO}}$ was calculated to be 0.0088. Drag coefficients for the wing and combined fuselage/engine installation were determined based on the calculated propeller thrust of 346.3 lbs. For take-off, the portion of the total thrust due to the aerodynamic drag was calculated from the scaled drag coefficients and subtracted from the calculated propeller thrust to define the portion of the propeller thrust due to rolling friction and aircraft acceleration which was assumed to be constant with propeller diameter. Table IE summarizes the calculations used to define the Debonair performance requirement with varying propeller diameter. Flyover thrust was estimated using the scaled drag coefficients. The flyover performance requirement vs propeller diameter was estimated from the calculated propeller thrust at 7 foot diameter and the estimated delta drags for the 6.5 and 6.0 foot diameters. The take-off aerodynamic drag calculation also included a constant drag added for the landing gear, elevator, and flap drags which was equal to 88 lbs. Estimated propeller thrusts labeled (1) in Table IE were based on calculated delta aerodynamic drags at 6.5 and 6.0 foot propeller diameters.

Light Twin Aircraft - Beech Duchess 76

For the Duchess aircraft in level flight, the aerodynamic drag was considered to be the total of the fuselage, wing, engine nacelle, and empennage drags. The wing drag coefficient was assumed to be equal to:

$C_{DW} = C_{DW_0} + \frac{(CL)^2}{\pi Ae}$ where the airplane efficiency factor, e, was assumed to be 0.9 and the effective aspect ratio for the Duchess was 7.98. Therefore:

$$C_{DW} = C_{DW_0} + 0.0443\ (CL)^2.$$

At the recommended cruise condition, C_{DW_0} was calculated to be 0.0048. Drag coefficients for the fuselage, wing, engine nacelle, and empennage were determined based on a calculated propeller thrust of 454 lbs for recommended cruise. Takeoff was handled in the same manner as for the Debonair aircraft. Table IIE summarizes the calculations used to define the Duchess performance requirements with propeller diameter.

Flyover thrust was estimated based on scaled drag coefficients from the recommended cruise condition. Thrust estimated for the 1000 ft flyover point was 5.5% lower than the calculated propeller thrust at the nominal propeller diameter. Estimated performance changes were based on calculated delta drags for each propeller diameter. The aerodynamic drag calculation for the takeoff conditions also included a constant drag for landing gear, elevator and flap drags which was equal to 92 lbs. Estimated propeller thrusts labeled (1) in Table IIE were based on calculated delta aerodynamic drags at 6.0 and 5.5 propeller diameters.

Heavy Twin Aircraft - DHC-6 Twin Otter

For the twin engine Twin Otter, the total aircraft drag was the sum of fuselage, wing, landing gear, engine nacelle, and empennage components. The wing drag coefficient was assumed to be equal to:

$C_{DW} = C_{DW_O} + \frac{(CL)^2}{\pi A e}$ where the airplane efficient factor, e, was assumed to be 0.9 and the effective aspect ratio was 10.06.

$C_{DW} = C_{DW_O} + 0.03516 \times (CL)^2$

C_{DW_O} was calculated to be 0.0056 at cruise for the Twin Otter. Drag coefficients were determined based on a calculated thrust for 2 propellers of 1963 lbs. The take-off condition was handled in the same manner as for the single engine and light twin aircrafts. Drag levels calculated for flyover were in the order of 15-20% less than the calculated propeller thrust. A comparison of cruise and flyover conditions indicated that flyover was not a level flight condition; therefore, the aerodynamic drag would not equal the propeller thrust. For purposes of defining the flyover thrust requirements, only the aerodynamic drag portion of the thrust requirement was considered to vary with propeller diameter. Table IIIE summarizes the calculations used to define the Twin Otter performance requirements with propeller diameter. The required flyover and take-off performance versus propeller diameter was estimated by applying the calculated delta percent aerodynamic drag to the calculated propeller thrust levels. Values labeled (1) in Table IIIC were based on calculated delta aerodynamic drags at 7.5 and 8.0 foot propeller diameters.

General Comments

Agreement between calculated propeller thrust and calculated thrust levels could not be attained in all cases of presumably level flight. Flyover thrust for the single engine Debonair was overpredicted by the drag calculation while flyover thrust for the light twin Duchess and heavy twin Twin Otter aircraft were underpredicted. The effects of induced drag due to body interference were ignored except in the case of the wings and fuselage where a 5% increment was added for mutual interference. The drag of protuberances such as antennas, tabs, etc., was ignored for the single engine Debonair and light twin Duchess which were considered as reasonably clean configurations. For the heavy twin Otter aircraft a 7% allowance was made. Drag caused by engine inlet and cooling flow were not evaluated separately, but included in the nacelle or engine installation drag coefficients.

Based on the methodology outlined above, thrust requirements as a function of propeller diameter were defined for the single engine Debonair, the light twin engine Duchess, and the heavy twin engine DHC-6 Twin Otter. As seen from the above referenced figures in the discussion section of this report, the limiting flight condition is takeoff for the reference aircraft used in the study. If the required thrust had been assumed to be independent of diameter, the obtainable diameter reductions would have been greater than those actually used. Neglecting the effect of propeller diameter upon required thrust would have resulted in an optimistic prediction of the obtainable propeller noise reduction. To obtain the most realistic estimate of potential propeller noise reduction, the effect of propeller diameter upon required thrust was included in the study.

References

1. Perkins, Courtland D. and Hage, Robert E., "Airplane Performance Stability and Control," John Wiley & Sons, Inc., 8th Edition - June 1960.

2. Hoerner, Sighard F., "Fluid-Dynamic Drag," Published by Author, 2nd Edition - 1958.

TABLE IE

DEBONAIR PERFORMANCE - DIAMETER CALCULATIONS

Condition	q_o	q_{eg}	C_{DW}	C_{DC}	Calculated Drag-lbs	Propeller Thrust-lbs	% Delta Thrust Relative to 7 ft. Dia.	Propeller Dia.-ft.
Max Cruise	83.72	93.2	0.0112	0.0859	346.3	346.3	0%	7.0
Max Range	49.23	57.26	0.0162	0.0916	259.4	261.1	0%	7.0
Take-off	33.86	43.4	0.0243	0.0959	328.6	560.0	0%	7.0
Flyover	108.9	118.1	0.0095	0.0791	393.0	329.5	0%	7.0
Take-off	33.86	46.6	.0.0243	0.0959	338.6	570.0 (1)	+1.8% (1)	6.5
Flyover	108.9	125.3	0.0095	0.0791	403.8	340.0 (1)	+3.2% (1)	6.5
Take-off	33.86	51.1	0.0243	0.0959	355.2	586.0 (1)	+4.7% (1)	6.0
Flyover	108.9	139.0	1.0095	0.0791	424.4	360.8 (1)	+9.5% (1)	6.0

TABLE IIE

DUCHESS PERFORMANCE - DIAMETER CALCULATIONS

Condition	q_o	q_{eg}	C_{DW}	C_{DF}	C_{DN}	C_{De}	Calculated Drag-lbs	Propeller Thurst-lbs 2 Propellers	% Delta Thrust-lbs Relative to 6.33 ft Dia.	Propeller Dia.-ft
Recommended Cruise	69.76	76.52	0.009	0.11	0.18	0.009	446.0	454.0	0%	6.33
Flyover	89.51	96.19	0.0074	0.11	0.18	0.009	538.0	570.0	0%	6.33
Take-off	21.66	27.10	0.0487	0.11	0.18	0.009	432.0	1050.0	0%	6.33
Flyover	89.51	90.74	0.0074	0.11	0.18	0.009	541.5	573.7 (1)	+0.65%	6.0
Take-off	21.66	29.10	0.0487	0.11	0.18	0.009	439.9	1057.9 (1)	+0.75%	6.0
Flyover	89.51	92.91	0.0074	0.11	0.18	0.009	547.5	580.3 (1)	+1.8%	5.5
Take-off	21.66	32.98	0.0487	0.11	0.18	0.009	451.5	1069.5 (1)	+1.85%	5.5

TABLE IIIE

TWIN OTTER - PERFORMANCE - DIAMETER CALCULATIONS

Conditions	q_0	q_{eg}	C_{PW}	C_{DF}	C_{DN}	C_{DC}	$C_{D_{GR}}$	Calculated Drag-lbs	Propeller Thrust-lbs 2 Propelers	Propeller Dia.-ft	% Delta Thrust-Lbs Relative to 8.5 FT Dia.
Cruise	94.51	109.2	0.0125	0.105	0.135	0.0095	0.65	1933.3	1963.0	8.5	0%
Flyover	84.2	101.8	0.0137	0.109	0.137	0.0098	0.68	1829.2	2144.0	8.5	0%
Take-off	10.4	26.2	0.107	0.122	0.140	0.011	0.75	889.0	3440.0	8.5	0%
Flyover	84.2	105.1	0.0137	0.109	0.137	0.0098	0.68	1843.0	2160.0 (1)	8.0	+.75%
Take-off	10.4	28.2	0.107	0.122	0.140	0.001	0.75	919	3470.0 (1)	8.0	+.87%
Flyover	84.2	112.0	0.0137	0.109	0.137	0.0098	0.68	1875.0	2196.0 (1)	7.5	+2.4%
Take-off	10.4	31.6	0.107	0.122	0.140	0.011	0.75	972.0	3523.0 (1)	7.5	+2.4%